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ABSTRACT

Three different proposed propulsion systems which incorporate superconducting electric machines are described. Two of these systems utilize a propulsion system integrated ship service electrical system. A ship synthesis computer model is used to determine the gross characteristics, detailed weight and volumes, maximum sustained speed, and endurance fuel requirements for each proposed design.

Each of the designs is compared to a baseline ship, the FFG-7, to determine the impact of a superconducting propulsion system on gross characteristics, maximum sustained speed, endurance fuel, general arrangements, payload, vulnerability/survivability, risk, maintenance, and cost.

Final comparison of the proposed designs shows a 31% reduction in propulsion machinery weight for all candidates. The two superconducting/integrated designs show a 61% reduction in electrical machinery weight, a 6% reduction in total required volume, a 10% reduction in full load displacement, a 7% increase in maximum sustained speed, and an 8% reduction in fuel.

The results of this thesis document very impressive reductions in total weight and required volume. The superconducting propulsion systems described in this thesis will provide the designer with greater arrangement flexibility compared to conventional propulsion systems. Operationally, the superconducting/integrated systems contribute to a reduction in own ship's noise, maintenance costs, and operation costs. In addition, these proposed designs can provide a significant improvement in the vulnerability/survivability characteristics of the ship and allow the designer the option of increasing the ship's payload without increasing the size of the ship.

The major drawback of these proposed systems is the high level of risk inherent in their design. This is due to the uncertainty of system performance and to the potential hazards due to high electric currents and liquid helium.

AN IMPACT ANALYSIS OF SUPERCONDUCTING ELECTRICAL PROPULSION SYSTEMS ON NAVAL SHIP DESIGN

by

WILLIAM JOE YORK

B.A., MIAMI UNIVERSITY
(1970)

M.A.T., THE CITADEL
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NAVAL ARCHITECTURE TERMS

TERM or SYMBOL	DEFINITION
B	Beam (width) of hull. Measured at waterline unless otherwise specified.
BM	Distance from center of buoyancy to metacenter.
BSIC	Weight classification system. Composed of seven distinct weight groups plus the variable loads.
CODAD	A propulsion system type which combines two or more different size diesel engines as prime movers.
CODAG	A propulsion system type which combines both diesel engines and gas turbines as prime movers.
COGAG	A propulsion system type which combines two or more different size gas turbines as prime movers.
C_P	Prismatic coefficient. The design parameter which expresses the percentage of a prism of dimensions L,B,T which the underwater hull would occupy.
C_X	Midship section coefficient. The design parameter which expresses the percentage of a rectangle of dimensions B,T which the hull midship cross section would occupy.
D	Depth. The distance from the main deck to the keel baseline.
D 0	Depth at station 0.
D 10	Depth at station 10.
D 20	Depth at station 20
D_{avg}	Average depth of the main deck.

TERM or SYMBOL	DEFINITION
FLD	Full load displacement. The total weight of a ship including the variable loads.
GM	The distance from the vertical center of gravity to the matacenter.
KB	The distance from the keel to the center of buoyancy.
KG	The distance from the keel to the vertical center og gravity.
Light Ship Displacement	The total weight of the ship excluding the variable loads.
SFC	Specific fuel consumption. A measure-of fuel usage rate in lbs/hp-hr
SHP	Shaft horsepower.
SHPE	Shaft horsepower at endurance speed.
T	Draft. Distance from the keel base-line to the waterline.
VCG	Vertical center of gravity.
V_{END}	Endurance speed measured in knots.
Weight Margin	An allocation in tons for future growth.

INTRODUCTION

The utilization of electric motors for ship propulsion is by no means a modern technology. The earliest recorded use of electric propulsion for ships occured in Russia in 1893. Since then, large numbers of ships have been built with electric propulsion plants. In the 1920's, the aircraft carriers Saratoga and Lexington both utilized electric propulsion systems in the 176,000 horsepower range. The most successful and widespread use was seen in the diesel-electric submarines built before and during World War II. The lack of reduction gear cutting capacity during the war greatly increased the interest in electrical propulsion.(1)

The advantages of electric propulsion are very attractive. Among these are:

(a) The elimination of direct coupling of the prime mover to the propeller allowing for greatly reduced shafting runs and improved casualty control.

(b) The elimination of reduction gears and their inherent acoustic signature.

(c) Increased flexibility in locating prime movers since there is no requirement for all propulsion components to be "in line".

(d) Shaft speed can be controlled more accurately.

(e) The designer has greater flexibility in selecting the number and size of prime movers. The utilization of

combined plants (CODAD, CODAG, COGAG, etc.) are more practical and easier to design.

(f) Prime movers can be operated at their maximum efficiency while varying shaft speed without a controllable pitch propeller.

(g) Electric motors and generators are simple in construction, easy to operate, and have an exceptionally fine maintenance history.

In spite of the seemingly overwhelming advantages, electric propulsion systems are not being used in any recent surface or submarine combatant designs. The reasons for this are few but overriding. The three most common difficulties associated with electric propulsion are:

(a) Higher acquisition costs than competitive alternatives.

(b) Considerably greater weight and volume requirements than alternatives.

(c) Higher transmission losses overall, reflecting a lower system efficiency and higher fuel usage than alternatives.

Of the three listed above, the second causes the most difficulty for the ship designer. Naval architects and ship designers are being asked to design ships with more and more payload while keeping the displacement, cost, and manning down. As a result, the designers are forced to forfeit the advantages of electric propulsion in favor of light weight, low volume propulsion systems. The advent of the marine gas turbine has

aided the designer considerably. However, he is still constrained with the requirement of "in line" propulsion components and the associated loss of flexibility in arrangement and location of the main machinery spaces.

In 1911, Kammerling Onnes discovered that the resistivity of certain conducting materials essentially vanished at temperatures near absolute zero. Because of this extraordinary electrical property he called this new state the "superconducting" state and called the materials "superconductors". Since then, over two dozen superconducting elements and compounds have been identified. Subjecting these materials to a very low temperature is a necessary but not sufficient condition to ensure superconductivity. The superconducting state can be destroyed by application of a sufficiently strong magnetic field or passage of a sufficiently large current. The temperature below which the material is superconductive is called the critical temperature and the magnetic field above which the material losses superconductivity is called the critical magnetic field. Upon violating either of these critical parameters the shift from the superconducting state to the normal conducting state is essentially instantaneous.

The state of extremely low resistivity implies that losses could be greatly reduced. This low loss condition indicated that electric motors and generators could be built to higher ratings for smaller physical size. However, before practical superconducting electrical devices could be built it was necessary to identify at least one material with a reasonably

attainable critical temperature and a high critical magnetic field. Such a material, a niobium tin compound, was discovered in 1961.

Considerable research has been conducted in the recent past in both machine design and superconductor development. Recently a method was developed to produce extruded copper wire with embedded niobium fibers for use in machine coil windings. Current development efforts are directed at improving the very high density current collectors. Collectors for large machines must be capable of handling current densities of 3,000 to 9,000 kiloamps per square meter. The major concern of the machine designers is to reduce as much as possible the chance of catastrophic failure of the machine when, for some reason, there is a loss of supercooling refrigeration.

The advent of superconducting machinery for shipboard use indicates an order-of-magnitude savings in weight, reduced volume, and the distinct possibility of reduced costs. The end result is a propulsion system having all the advantages of electric power without all the classic disadvantages of high weight, large volume, and high cost.

The refrigeration units needed to provide the supercooling are the most developed components in the system. The principles of operation and design are well understood and units of sufficient capacity are commercially available. Additional developmental effort is needed to marinize these units in order to provide suitably compact and quiet units. Specific

details concerning weight and volume of shipboard units will be developed in chapter two of this thesis.

An interesting aspect of electrical propulsion which is getting more and more attention is that of integrating the ship service electrical system with the ships propulsion system. None of the present day major combatant designs take advantage of electrical integration. Most designs today utilize separate gas turbine or diesel generators for ship servive electrical power. This creates additional difficulty for the designer since he must find additional deck space, internal volume, and provide for additional ducting. These installations also contribute to increasing the ship's weight and cost. The marriage of light weight, high efficiency, large capacity gas turbines with superconducting motors and generators could eliminate the need for separate ship service electrical generating equipment. This integration could be accomplished with steam turbines as well, and hence, find application with nuclear propulsion plants. The design of an integrated ship service electrical system will be discussed in detail in chapter three of this thesis.

CHAPTER 1

BASELINE SHIP DESCRIPTION

1.1 Introduction

The intent of this thesis is to analize the impact of the application of superconducting propulsion systems on naval ship design. One realistic method of analysis, and the one selected here, is to compare a well defined baseline ship without superconducting propulsion to a model ship with superconducting propulsion. In order to make a valid comparison, the proposed model must conform to the same design philosophy, requirements, and constraints that guided the development of the baseline ship. In order to judge one ship as being "as good as" or "better than" another ship, it is imperative that the two ships have the same mission requirements.

The baseline ship selected for the comparative analysis is the FFG-7. This ship is a U.S. Navy guided missile escort vessel. This ship was designed for entry into the fleet in the mid 1970's and represents a modern design. The primary reasons for selecting this baseline are threefold.

First, since this ship is a recent design, it represents, in many ways, the present day trend in naval ship design of minimizing ship acquisition cost. Historically, naval ship design has shifted from performance optimization to minimizing life cycle cost to minimizing acquisition cost.

Secondly, the FFG-7 is well documented and a good deal of

information, data, and specifications have been published. Since this ship class is still under construction, information concerning design deficiencies is continually being reported.

Thirdly, the FFG-7 presented an unusually demanding task to the designers. In addition to a broad mission requirement, the following design constraints were imposed.

(1) The follow-on ships must not exceed an acquisition cost of 45 million dollars each (1974 $).

(2) The ships full load displacement must not exceed 3,400 tons.

(3) The total manning must not exceed 185 men.

(4) The ship must utilize "off-the-shelf", standardized equipments.

It should be noted that the FFG-7 class ships do not conform to constraints (1) and (2) listed above. The full load displacement has increased to 3,617 tons. The acquisition cost exceeds the cost specified primarily due to the addition of equipment not originally requested. In addition, the onboard maintenance requirements were underestimated and there is a real possibility that the manning level will have to be increased over the 185 man constraint.

1.2 Baseline Ship Characteristics

The comparative analysis will be conducted in chapter five of this paper. The baseline ship characteristics and weights necessary for the analysis are shown in tables 1.1 and 1.2.

Length (BP)	408 ft
Length (OA)	445 ft
Draft (full load)	15.0 ft
Beam (max)	46.9 ft
Light Ship Displacement	2,777 tons
Full Load Displacement	3,617 tons
Manning	185
Propulsion	(2) LM 2500 Gas Turbines 40,000 SHP total
	(1) Shaft
	(1) Controllable Pitch Propeller
Electrical	(4) 1000 KW Diesel Generators
Armament	(1) MK 13 Guided Missile Launcher
	(1) 76 mm Gun Mount
	(1) CIWS
	(1) Lamps III Helo
	(2) ASW Torpedo Tube Groups

PRINCIPLE CHARACTERISTICS[2]

Table 1.1

GROUP #	DESCRIPTION	WEIGHT(tons)	WEIGHT FRACTION
1	Hull Structure	1248.55	.345
2	Propulsion	287.04	.079
3	Electric Plant	195.72	.054
4	Command and Control	116.13	.032
5	Auxillary Systems	440.01	.124
6	Outfit and Furnishings	318.78	.088
7	Armament	93.54	.025
	Light shipw/o Margin	2708.77	.748
	Margin	68.91	.019
	Full Load Displacement	3617.47	1.0

A complete listing of all three digit weight groups required for the analysis can be found in appendix I.

GROUP WEIGHTS(3)

Table 1.2

CHAPTER 2

SUPERCONDUCTING PROPULSION SYSTEM

2.1 Propulsion Plant Description

The proposed superconducting propulsion system is shown schematically in figure 2.1. The major components are as follows:

(2) LM 2500 marine gas turbines

(1) Superconducting DC propulsion motor

(2) Superconducting DC propulsion generators

(1) Cryogenic liquid helium cooling system

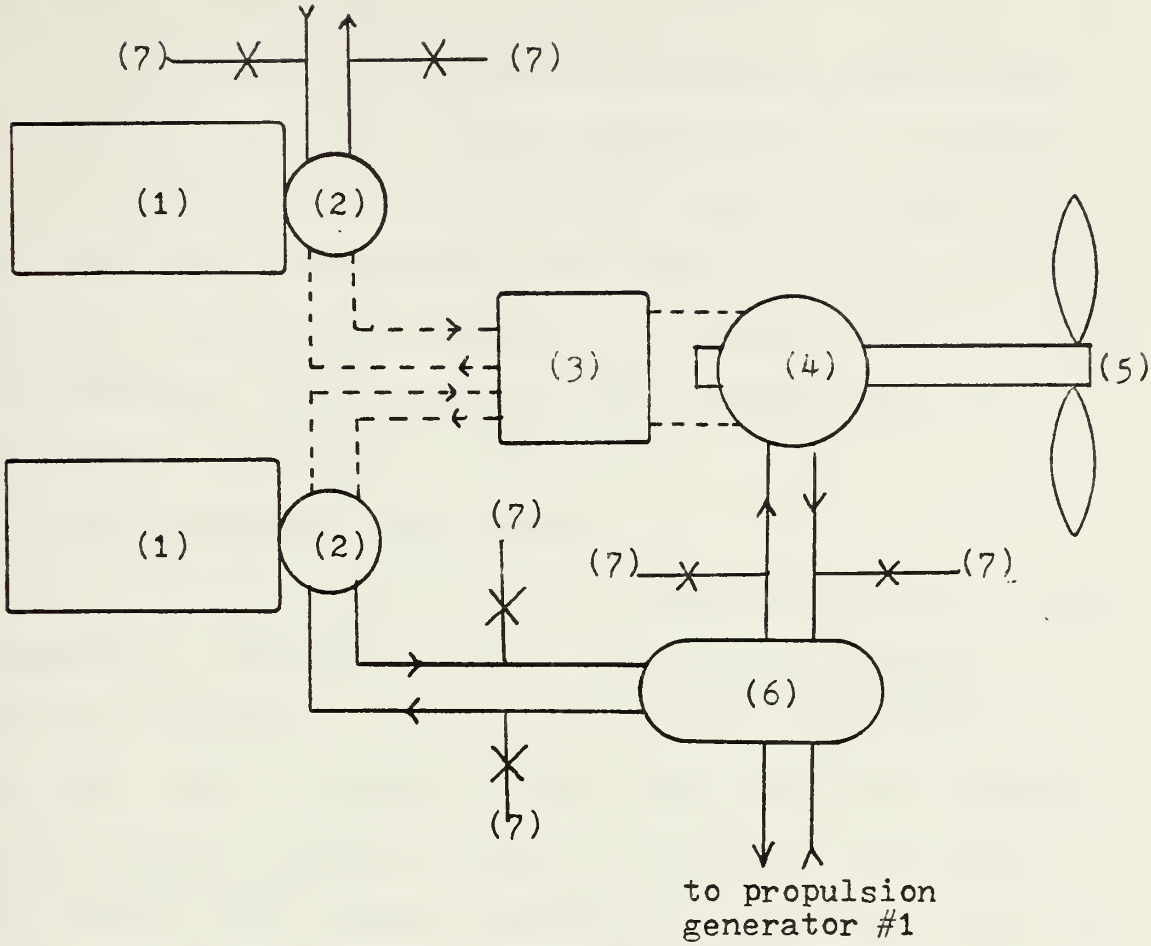
(1) Fixed pitch propeller

(1) Electric propulsion distribution and control panel

(1) Liquid helium distribution and control subsystem

With the exception of the propulsion motors and generators, all of the major components listed above are within present production capabilities. There has been sufficient study and experimentation to clearly demonstrate the feasibility and producibility of the superconducting components. The risks associated with the utilization of these equipments will be discussed in chapter 5.

The data necessary to establish the performance characteristics and physical dimensions for the superconducting components and the cryogenic cooling system was extracted from reports published by David Taylor Naval Ship Research and Development Center (DTNSRDC), Annapolis, Maryland.[5-9] The data contained in these reports is consistent with reports



(1) LM 2500 gas turbine
(2) superconducting DC propulsion generator (20,115 HP)
(3) electric propulsion distribution and control panel
(4) superconducting electric propulsion motor (40,230 HP)
(5) fixed pitch propeller
(6) cryogenic refrigeration system
(7) portable cooldown unit connections
------------- electrical flow path
_____________ coolant flow path

SUPERCONDUCTING PROPULSION SYSTEM BLOCK DIAGRAM

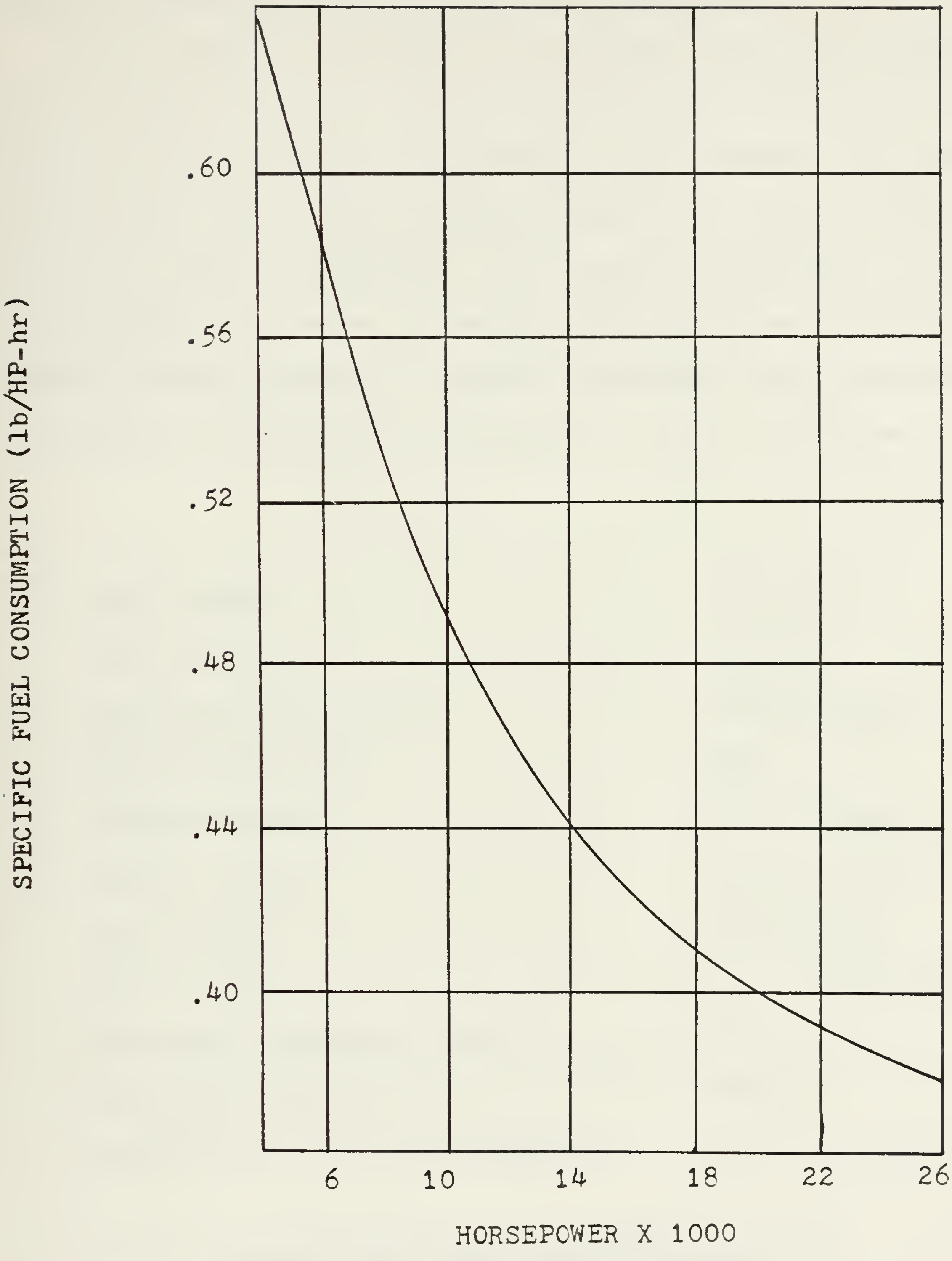
Figure 2.1

published by both Westinghouse and M.I.T.

The components in the proposed propulsion plant were sized to match the existing SHP requirements for the FFG-7 plus the additional power required to supply the ships service electrical requirements. The specific function and description of each major component is discussed in the following subchapters. The integrated ship service electrical system will be discussed in chapter 3.

2.1.1 LM 2500 Marine Gas Turbine

Two of these prime movers are installed in a split plant arrangement. These are the same prime movers presently installed in the FFG-7. Each turbine is rated at 22,880 HP at 3,600 RPM. This is slightly higher than the FFG-7 rating due to the electrical system integration and hence, the need to drive an additional normal conducting AC generator. Each turbine is coupled directly to the tandem generators. All clutches and reduction gears have been eliminated and there are no mechanical connections between the turbines and the propeller shaft. The LM 2500 operates on gaseous fuel, JP4/JP5, marine diesel, or heavy distillate fuel. The specific fuel consumption (SFC) at 22,800 HP is .39 lbs/HP-hr. The SFC graph for the LM 2500 for various power levels is shown in figure 2.2. As seen from the graph, the SFC improves as the power level increases.



LM 2500 SPECIFIC FUEL CONSUMPTION (4)

Figure 2.2

2.1.2 40,230 HP Shielded Superconducting Motor

The DC propulsion motor is an acyclic motor utilizing liquid metal collectors and a superconductive winding in a hexpole, shaped field configuration. This machine is a scaled up version of the 3,000 HP machine presently being evaluated by the U.S. Navy at DTNSRDC. This machine represents an order of magnitude improvement in weight and volume over normal conducting electric motors. Specific operating characteristics and physical dimensions are detailed in table 2.1 below.

rated power	40,230 HP
rated voltage	300 VDC
rated maximum current	100,000 amps
rated maximum RPM	180
maximum diameter	73.2 inches
maximum length	145.2 inches
total weight	36.85 tons
total volume	356.63 cubic feet
efficiency (maximum power)	97.3%
efficiency (½ power)	98.6%
liquid helium cooling requirement	5.4 liters/hour

PROPULSION MOTOR CHARACTERISTICS [7]

Table 2.1

2.1.3 20,115 HP Shielded Superconducting Propulsion Generator

This machine is identical in principle to the propulsion motor. Each propulsion generator is driven by a separate gas turbine at a constant speed of 3,600 RPM. A DC generator was chosen over an AC generator with a rectification system because the DC generator is smaller, lighter, and more efficient. Specific characteristics and physical dimensions are detailed in table 2.2 below.

rated output	20,115 HP
voltage output	300 VDC
maximum output current	50,000 amps
weight	3.19 tons
volume	30.36 cubic feet
length	5.38 feet
liquid helium cooling requirement	2.9 liters/hour

PROPULSION GENERATOR CHARACTERISTICS [8]

Table 2.2

2.1.4 Liquid Helium Refrigeration System

The single most critical auxillary in the propulsion system is the cryogenic cooling system. The superconducting windings in the propulsion motor and generators require an

environment at a temperature of liquid helium and at one atmosphere pressure. The refrigeration system is designed to maintain the superconducting windings at $4.4^{\circ}K$ during and between missions. Hence, the motor and generators will require cooldown from $300^{\circ}K$ only after planned overhaul or maintenance action. The major components of the cooling system are as follows:

(1) Oil flooded screw type compressor (online)

(1) Installed compressor spare

(3) Three piston expansion stage liquifiers with interstage heat exchange (online)

(1) Installed liquifier spare

(1) Portable cooldown unit with single piston expansion stage

Specific operating characteristics and physical dimensions are shown in table 2.3.

2.1.5 Propeller

The propeller utilized in the propulsion system is a 5 bladed, fixed pitch type. Shaft reversal can easily be accomplished with a DC motor by reversing the power leads. This ability to reverse the shaft negates the necessity to employ a controllable reversible propeller (CRP) and its associated control system.

Historically, the CRP type propellers have been troublesome. In addition, the CRP type is less efficient and heavier than an equivalent fixed pitch propeller. A brief com-

parison is shown in table 2.4.

2.1.6 Electric Propulsion Distribution and Control System

This subsystem allows for the monitoring and control of the propulsion motors and generators. The control system will select the generator source, contol the generator excitation, monitor the motor and generator performance, and distribute the propulsion power to the motor.

An integral part of the distribution and control subsystem is the braking resistor group. Braking resistors are required to absorb the large transient currents during shaft reversal. The resistors are air and water cooled to prevent overheating.

The high current, typically 100,000 amps, characteristic of large superconducting homopolar machines require highly efficient switchgear for propulsion motor reversal. Experimental model switchgear constructed at DTNSRDC using Multilam material in the contact regions is 5-10 times smaller and lighter than equivalent commercially available switchgear. The use of liquid cooled, coaxial transmission lines with such switchgear results in a lightweight, compact system. The exact weight of the transmission system cannot be determined at this stage. However, a reasonable estimate based on a typical arrangement would be approximately 9 tons.

2.1.7 Liquid Helium Distribution and Control System

The function of this system is to monitor and control the distribution of the liquid helium coolant to the super-

COMPONENT	WEIGHT (tons)	VOLUME (ft^3)	# INSTALLED
Compressor	1.1	46.78	1
compressor (spare)	1.1	46.78	1
Liquifier	1.08	52.59	3
Liquifier (spare)	.36	17.65	1
Cooldown unit	.39	35.31	1
Valves, piping, etc.	.29	26.48	------
Total Weight	4.32	-----	
Total Volume	-----	243.62	

Input power required: 81 KW

Total Flow: 11.2 liters/hour @ 4.4°K

LIQUID HELIUM COOLING SYSTEM CHARACTERISTICS[9]

Table 2.3

PARAMETER	CRP	FIXED PITCH
Rated Power	40,000 HP	40,230 HP
Maximum RPM	160	180
Open Water Efficiency	70%	73%
Diameter	17 feet	17 feet
Weight	31 tons	18 tons

PROPELLER CHARACTERISTICS

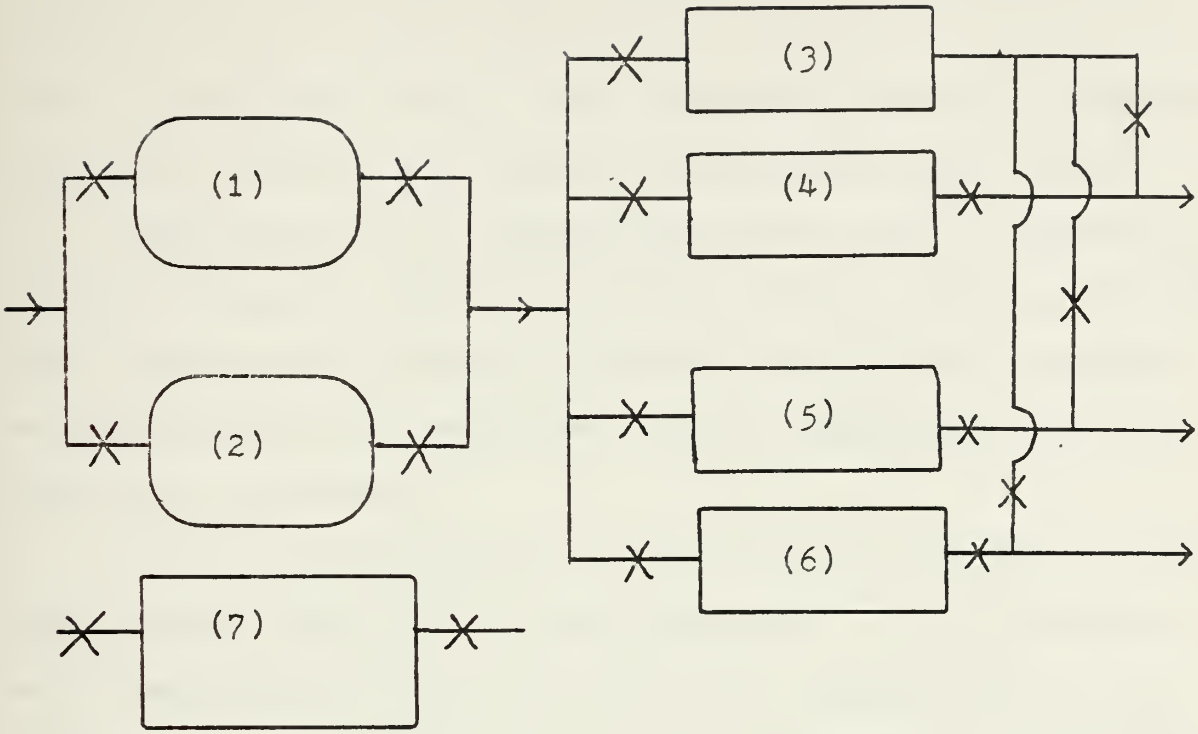
Table 2.4

conducting motors and generators. Inherent in this system is a rapid cross connect capability for casualty control. Rapid response to casualties is accomplished using installed spares and valve actauted cross connects. Figure 2.3 schematically illustrates the component arrangement and the location of the cross connect valves. The function of the portable cooldown unit will be discussed in chapter 2.2.

2.2 Propulsion System Operation

The propulsion system can be operated in either a split plant or combined plant lineup depending on the power required, casualty conditions, or maintenance requirements. Either LM 2500 operated in a single plant lineup is capable of delivering sufficient power for a cruise speed of 20 knots. The control of the gas turbines is designed to provide automatic power regulation and fuel proportioning based on operational speed requirements. The gas turbines will be operated at a constant speed of 3,600 RPM. Each turbine module is noise insulated and equipped with a Halon 1301 fire extinguishing system. The entire system is sufficiently automated to allow two men to control normal operation.

Each gas turbine drives a superconducting DC propulsion generator which in turn provides 300 VDC power to the propulsion distribution and control subsystem. The maximum current output from each generator is 50,000 amps. The necessary cryogenic cooling is provided by the liquid helium refrigeration system at a flow rate of 11.2 liters/hour at full power.



(1) Compressor
(2) Compressor (installed spare)
(3) Liquifier (installed spare)
(4) Liquifier (motor)
(5) Liquifier (generator #1)
(6) Liquifier (generator #2)
(7) Portable Cooldown Unit
X Isolation Valves

COOLING FLOW CONTROL SYSTEM

Figure 2.3

The generated DC power is delivered to the propulsion distribution and control subsystem via the water cooled coaxial transmission lines. This subsystem selects the generator source and controls and monitors the system's performance.

Associated with the distribution and control subsystem is a group of dynamic braking resistors. These resistors are utilized during shaft reversals to absorb the transient currents and thus prevent the generators from overspeeding while the propeller is unloaded.

The superconducting DC propulsion motor is capable of delivering up to 40,230 HP to the propeller. At full power the motor requires 300 VDC at 100,000 amps. Supercooling is provided by the same unit that services the propulsion generators. At full power, the motor requires a coolant flow of 5.4 liters/hour.

The propulsion motor drives a conventional fixed pitch propeller at a maximum rotational speed of 180 RPM at full power. This propeller replaces the CRP type presently used on the FFG-7. The specific propeller cannot be determined at this stage but its diameter will be 17 feet.

The heart of this propulsion system is the liquid helium refrigeration system. This system is designed to deliver a flow rate of 11.2 liters/hour at one atmosphere of pressure. The compressor output is compressed helium at ambient temperature and 11 atmospheres of pressure. The compressed gas is delivered to each of three online liquifiers which reduce the

the temperature to $4.4^{\circ}K$. Each liquifier services a separate superconducting machine.

Rapid casualty control is a necessity and requires installed redundency. The installed spare compressor and liquifier can be quickly put into service through a network of cross connect valves. Studies indicate that the superconducting machines could operate for approximately 5 hours with a loss of coolant so long as the machine remained closed and pressure tight. However, this capability has not been demonstrated on full sized machines under actual operating conditions.

The superconducting machines are maintained at $4.4^{\circ}K$ at all times. In the event of a casualty or if routine maintenance is required, the machine must be cooled down again from ambient to operating temperature as quickly as possible. To assist in this cooldown, a portable unit is installed on the warm machine. Cooling from ambient to operating temperature is a lengthy process requiring approximately 50 hours for the propulsion motor and approximately 5 hours for the propulsion generator. The time breakdown for a typical cooldown sequence is shown in table 2.5 on the following page.

PROCESS	MOTOR	GENERATOR
Installation of cooldown unit	.5 hr	.5 hr
$300^{o}K$ to $100^{o}K$ (constant speed)	31 hr	2.5 hr
$100^{o}K$ to $15^{o}K$ (constant flow)	6 hr	.5 hr
Liquifier installation	.5 hr	.5 hr
$15^{o}K$ to $4.4^{o}K$	12 hr	1 hr
TOTAL	50 hr	5 hr

COOLDOWN SCHEDULE[9]

Table 2.5

CHAPTER 3

INTEGRATED SHIPS ELECTRICAL SYSTEM

3.1 Introduction

An integrated ships service electrical system is one which utilizes a common prime mover to drive both the propulsion components and the electrical generating components. The definition of an integrated system does not preclude the use of a mechanical drive propulsion system, but studies have shown that maximum advantage is gained when the integration is done with electrical propulsion.(10)

The most recent naval ship designs use either gas turbine generators or diesel driven generators to provide ships service electrical power. The Spruance class destroyers (DD 963) utilize three Allison 501-17K gas turbine generators and the FFG-7 class use four Detroit 16V-149-TI diesel generators. The ship designer is faced with the problem of finding space and accepting the weight for these components and their associated ancillaries. In the case of the FFG-7 the weight penalty for these generators is in excess of 100 tons and the space allocated amounts to several thousand cubic feet.

The major advantages of an integrated electrical plant are as follows:

(1) If the SFC of the ships service prime mover is greater than the SFC of the propulsion prime mover then greater fuel economy can be realized.

(2) There will be a considerable reduction in both acquisition cost and maintenance requirements.

(3) Reducing the number of ship service electrical generators will contribute to greater frequency and voltage stability since the number of units operating in parallel is reduced.

(4) A reduction in the ship's acoustic and infrared signature can be achieved.

(5) There will be more volume for payload space assignment.

(6) A reduction in manning can often be achieved.

The extent to which these advantages are realized will vary from ship to ship. In the case of the FFG-7, the integration will allow for the removal of the four diesel generators and their associated ancillaries. A complete analysis of the impact will be done in chapter 5 of this thesis.

Figure 3.1 schematically illustrates the integration of the ship service electrical generating equipment into the superconducting propulsion system.

3.2 Integrated Electrical System Description

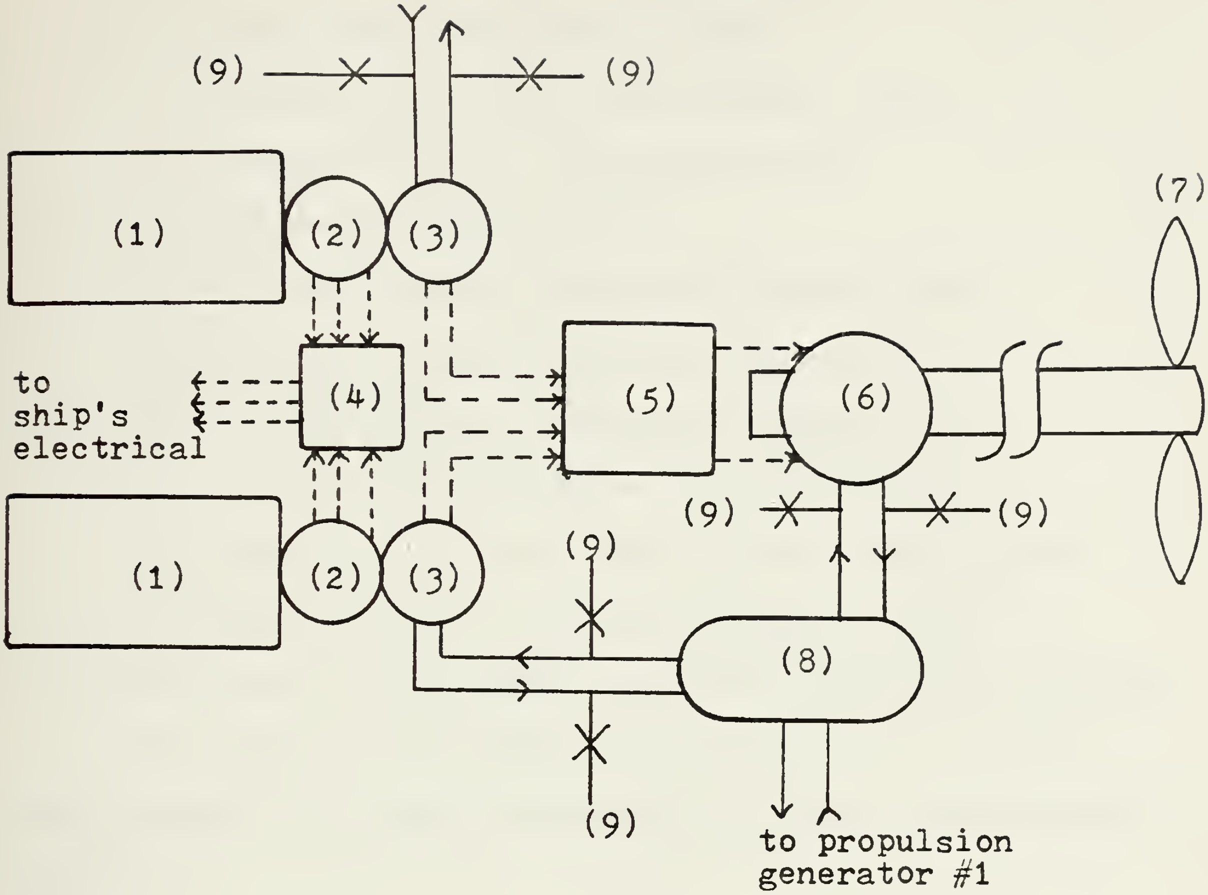
The major components of the electrical system are as follows:

(1) 2000 KW Normal Conducting AC Generator (starboard)

(2) 2000 KW Normal Conducting AC Generator (port)

(3) Ship Servive Electric Plant Control Panel

(4) Shore Power Breaker Panel



(1) LM 2500 gas turbine
(2) ship service AC generator (2000 KW)
(3) superconducting propulsion DC generator (20,115 HP)
(4) ship service electrical distribution and control panel
(5) electric propulsion distribution and control panel
(6) superconducting electric propulsion motor (40,230 HP)
(7) fixed pitch propeller
(8) cryogenic refrigeration system
(9) portable cooldown unit connections

---------- electrical flow path

―――――― coolant flow path

SUPERCONDUCTING INTEGRATED PROPULSION SYSTEM BLOCK DIAGRAM

Figure 3.1

(5) Port Non-Vital Load Breaker Panel

(6) Port Vital Load Breaker Panel

(7) Starboard Non-Vital Load Breaker Panel

(8) Starboard Vital Load Breaker Panel

(9) 400 Hertz Breaker Panel

(10) 400 Hertz Static Frequency Converter #1

(11) 400 Hertz Static Frequency Converter #2

(12) 400 Hertz Static Frequency Converter #3

(13) 400 Hertz Distribution and Control Panel

(14) Output to Port Non-Vital Distribution System

(15) Output to Port Vital Distribution System

(16) Output to Starboard Non-Vital Distribution System

(17) Output to Starboard Vital Distribution System

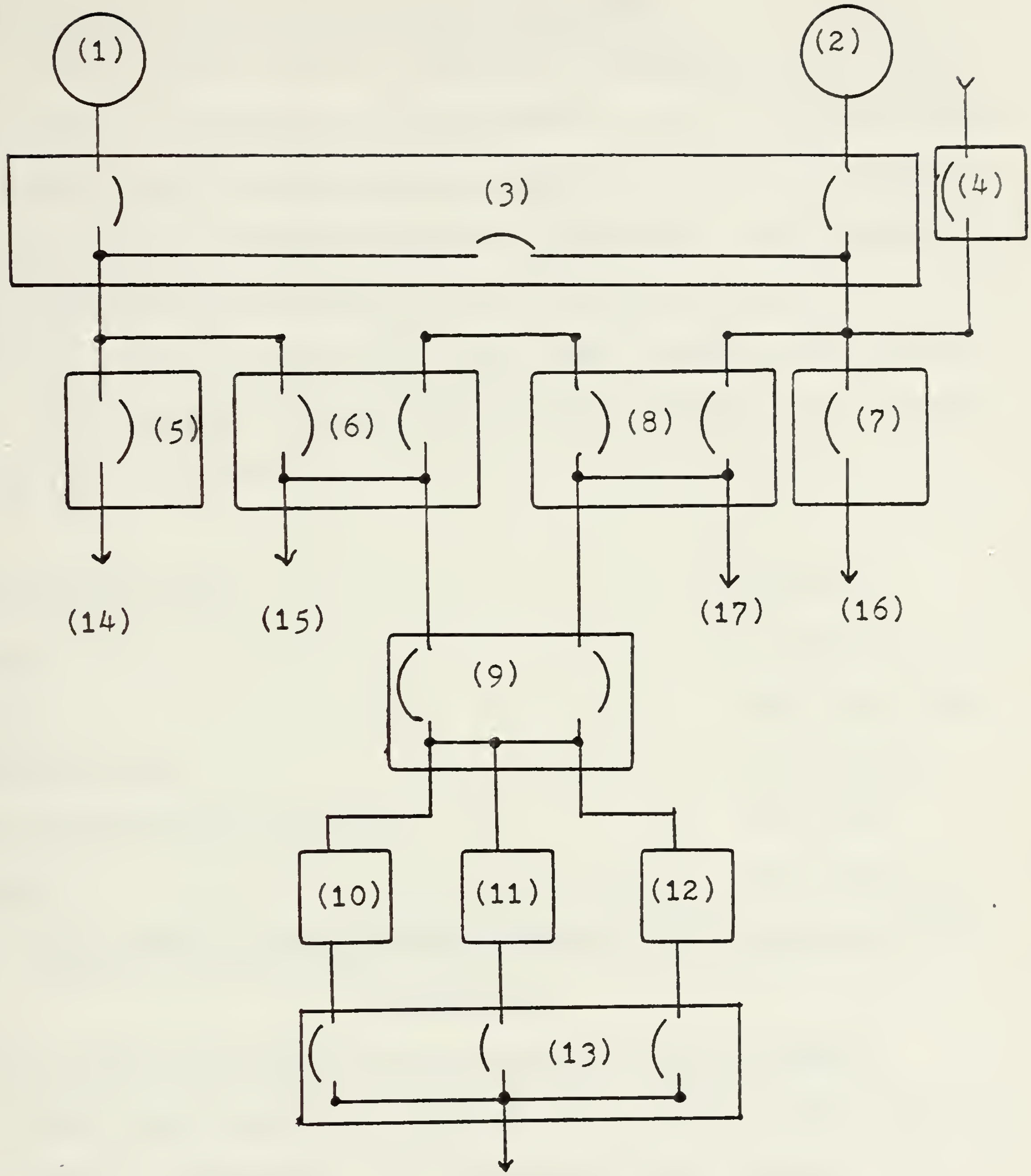
The interfacing of these components is shown schematically in figure 3.2.

The 60 hertz electrical load requirements for the FFG-7 for various operating conditions are listed in table 3.1. The maximum 400 hertz requirement is less than 150 KW.

CONDITION	LOAD (KW)
24 Hour Average	1300
Normal Cruise on 10^{o}F Day	2400
Battle Load	1800

FFG-7 60 HERTZ ELECTRICAL LOAD REQUIREMENTS

Table 3.1



60 HERTZ and 400 HERTZ ELECTRICAL DISTRIBUTION SYSTEM

Figure 3.2

3.2.1 Ships Service Electrical Generators

The two ships service electrical generators are normal conducting AC generators each driven by a LM 2500 gas turbine in tandem with the propulsion generators. The AC generators are driven at a constant speed of 3,600 RPM. Each generator has a maximum rated output of 2,000 KW and is designed to deliver 60 hertz, 3 phase, 440 volt power during normal operation. The specific characteristics and dimensions are shown in table 3.2 below.

Rated Power (max)	2000 KW
Weight	7.38 tons
Volume	90 cubic feet
Diameter (max)	65 inches
Rotational Speed (constant)	3600 RPM
Length	78 inches

SHIPS SERVICE ELECTRICAL GENERATOR CHARACTERISTICS[11]

Table 3.2

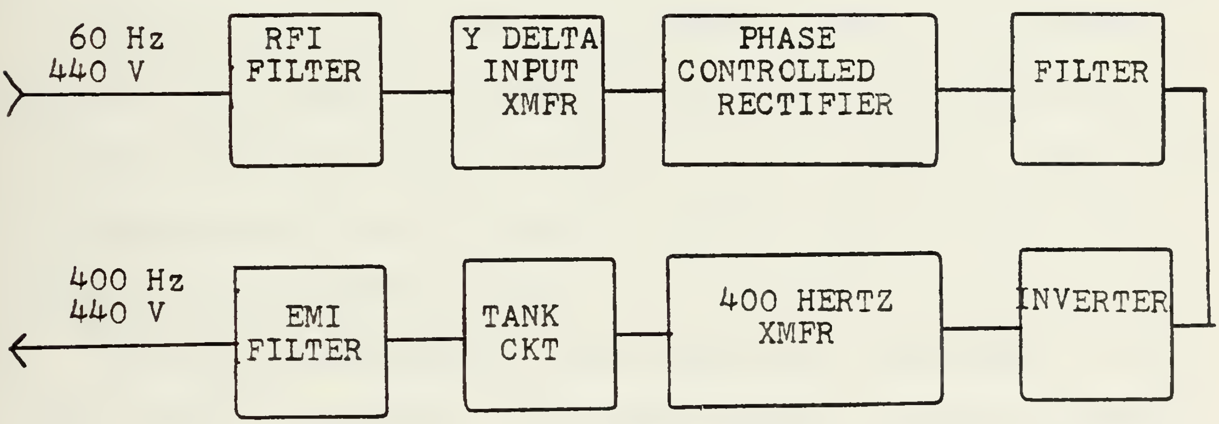
3.2.2 Ships Service Electrical Control Panel (SSECP)

The output from the ships service turbine generators is delivered to the SSECP. This control panel provides for the monitoring and control of the ships electrical system. The SSECP automatically provides feedback to the LM 2500 fuel feed system, provides shutdown for under and overspeed conditions, high and low frequency, high and low voltage, electrical system grounds, and provides the mechanism for generator connec-

tion and cross connection via the TG and TG-TG tie breaker. The output from the SSECP id delivered to the port and starboard, vital and non-vital breaker panels.

3.2.3 400 Hertz Static Frequency Converters

Aside from switchboards, breaker panel, rectifiers, and transformers, the last major components in the electrical system are the 400 hertz static frequency converters. These devices are designed to convert 60 hertz, 440 volt input to 400 hertz, 440 volt output. The static frequency converters replace the more commonly used motor-generator sets. The FFG-7 has three static converters installed each with a maximum rating of 150 KW. A functional block diagram of a typical static frequency converter is shown in figure 3.3 below.



BLOCK DIAGRAM of 60/400 HERTZ STATIC FREQUENCY CONVERTER

FIGURE 3.3

3.3 Ships Service Electrical System Operation

Ship service electrical generator lineup is controlled at the SSECP via the turbine generator (TG) breakers. If only one generator is needed or desired, the idle generator can be secured by opening its TG breaker and the on-line generator can supply both the port and starboard busses through its TG breaker and the TG-TG tie breaker. In all but severe cold weather conditions one generator can supply the entire ships service electrical demand. The synchronization and monitoring of the generators is done at the SSECP.

The output of the SSECP is delivered to the port and starboard, vital and non-vital breaker panels. System cross connection during one generator operation is achieved via the cross connect breaker located on the port and starboard vital breaker panels.

Output from the four major breaker panels is delivered to the vital load switchboards, non-vital load switchboards, and the 400 hertz breaker panel for distribution. Shore power is provided via the shore power breaker panel to the vital breaker panels while in port.

The 400 hertz breaker panel delivers input power to the three static converters. 400 hertz power is then delivered to system loads via the 400 hertz control and distribution panel. This panel also monitors and controls the operation of the static frequency converters. One on-line converter is sufficient to meet all the 400 hertz power demands.

All AC voltage reduction is done locally in the distribution system. DC power requirements are provided for by local rectifiers and DC power supplies.

Operation and monitoring of the entire ships service electrical system can be done by one man stationed at the SSECP. It is expected that in the normal cruising mode only one LM 2500 would be on-line providing sufficient power to drive its associated ships service and propulsion generator. The FFG-7 should be capable of making about 80% of its maximum speed and meeting 100% of the electrical demands with a one turbine lineup.

CHAPTER 4

TWIN SCREW, INTEGRATED PROPULSION SYSTEM

4.1 Introduction

The propulsion plant and electric plant described in chapters 2 and 3 respectively are for single shaft designs. Since the FFG-7 is a single shaft ship, the previously proposed systems most closely resemble the present installation. However, for the sake of completeness and in an attempt to fully maximize the benefits of a superconducting, integrated propulsion plant, a third candidate will be analized.

Historically, twin screw ships offer better manuverability, improved reliability, and greater operational flexibility than single screw designs. FFG-7 design constraints precluded the use of a twin screw arrangement because of the inherent greater weight and volume requirements associated with these designs. The anticipated weight and volume reductions due to the superconducting, integrated propulsion installation may make a twin screw propulsion plant a viable alternative.

A twin screw, superconducting, electrically integrated propulsion plant will be described in the following subchapter and analized in chapter 5 with the two previously proposed systems. A twin screw, non-integrated system will not be evaluated.

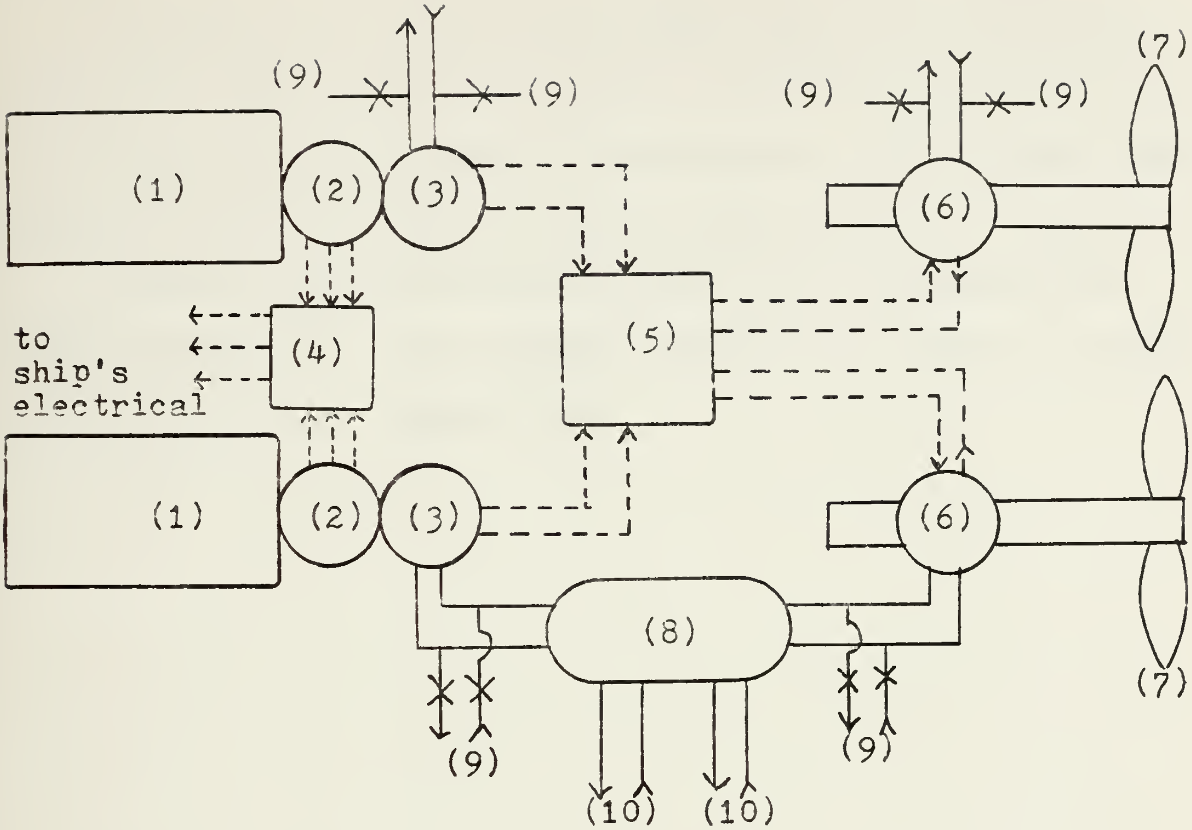
4.2 Propulsion Plant Description

The twin screw propulsion plant is shown schematically

in figure 4.1. As can be seen by comparing with figure 3.1, the only differences are the addition of a second shaft, propeller, and propulsion motor. The single shaft system uses one 40,230 HP motor and the twin shaft system uses two 20,115 HP motors. The gas turbines, ships service electrical generators, propulsion generators, and cryogenic refrigeration system are identical in design and function. Minor design modifications in the distribution and control subsystem will be necessary.

In the normal cruise mode, one gas turbine, one propulsion generator, one ships service electrical generator, and both propulsion motors will be on-line. Either turbine/ generator system can drive either propulsion motor. For full power operation, each turbine/generator will drive a separate propulsion motor. As in the previously described plants, shaft reversal is accomplished by reversing power leads via the distribution and control panel. Hence, a single turbine/ generator can drive the two shafts in opposite directions by simply reversing power leads on one of the motors. The same type breaking resistor subsystem is required to absorb high transient currents during crashback evolutions.

Since the total required torque is now divided between two shafts, the propeller speed will increase to approximately 250 RPM and the propeller diameter will be decreased to approximately 12 feet. As with the previous designs, the propellers are 5 bladed, fixed pitch types.



(1) LM 2500 gas turbine
(2) ship service AC generator (2000 KW)
(3) superconducting propulsion DC generator (20,115 HP)
(4) ship service electrical distribution and control panel
(5) electric propulsion distribution and control panel
(6) superconducting DC propulsion motor (20,115 HP)
(7) fixed pitch propeller
(8) cryogenic refrigeration system
(9) portable cooldown unit connections
(10) liquid helium connections for starboard side components
------------ electrical flow path
__________ coolant flow path

<u>TWIN SCREW, SUPERCONDUCTING INTEGRATED</u>

<u>PROPULSION SYSTEM BLOCK DIAGRAM</u>

<u>Figure 4.1</u>

The reduction of the propulsion motor size will allow for a more rapid cooldown process. Cooldown from ambient to $4.4^{o}K$ can be accomplished in approximately one half the time required for the 40,230 HP motor, approximately 24 hours.

Specific characteristics of the 20,115 HP propulsion motor, propellers, and cooldown schedule are shown in tables 4.1, 4.2, and 4.3 respectively.

Rated Power	20,115 HP
Rated Voltage	300 VDC
Maximum Current	50,000 amps
Maximum Diameter	36.6 inches
Maximum Length	72.6 inches
Total Weight	18 tons
Total Volume	45 cubic feet
Maximum RPM	250
Liquid Helium Cooling Requirement	2.7 liters/hour

20,115 HP PROPULSION MOTOR CHARACTERISTICS

Table 4.1

Rated Power	20,115 HP
Maximum RPM	250
Open Water Efficiency	73%
Diameter	12 feet
Weight	12 tons

PROPELLER CHARACTERISTICS

Table 4.2

Installation of Cooldown Unit	.5 hr
$300^{\circ}K$ to $100^{\circ}K$ (constant speed)	15 hr
$100^{\circ}K$ to $15^{\circ}K$ (constant flow)	3 hr
Liquifier Installation	.5 hr
$15^{\circ}K$ to $4.4^{\circ}K$	6 hr
Total:	25 hr

20,115 HP PROPULSION MOTOR COOLDOWN SCHEDULE

Table 4.3

CHAPTER 5

COMPARATIVE ANALYSIS

5.1 Introduction

The necessary data and design characteristics pertaining to the proposed superconducting propulsion systems was developed in chapters 2, 3, and 4. A complete listing of the modified BSIC weight groups is provided in appendix I. Specific weight data for the FFG-7 is provided in appendix II.

Three proposed modifications will be analized and evaluated. The three candidates are as follows:

Candidate #	Brief Description
1	single screw, superconducting electric propuslion, diesel generator ships service electrical system
2	single screw, superconducting electric propulsion, integrated ships service electrical system
3	twin screw, superconducting electric propulsion, integrated ships service electrical system

The major analytical tool to be used is a ships synthesis model[12] developed for the design of destroyer type combatants. A brief description of this synthesis model will be

given in subchapter 5.2. The specific input values and format for the three candidates are detailed in appendix III. A detailed listing of the output values for each candidate is provided in appendix IV.

The output of the ships synthesis model will be gross characteristics, area and volume data, stability data, maximum sustained speed, and endurance fuel requirements. The payload for all the candidates is identical and completely specified as an input to the program. This was done to ensure that the candidate ships have the same mission capability as the baseline FFG-7. The endurance for each candidate was specified to be 4,500 NM @ 20 knots. This too coincides with the FFG-7.

The analysis will center on nine comparative areas as follows:

(1) gross characteristics
(2) maximum sustained speed
(3) endurance fuel requirements
(4) general arrangements
(5) payload
(6) vulnerability/survivability
(7) risk
(8) maintenance
(9) cost

The three candidates will be compared in each of the above areas. The objective of the analysis is essentially twofold.

First to determine if any of the proposed candidates offer an improved design over the FFG-7. An "improved" design, in the context of this thesis, is one which provides a mission equivalent ship which meets or more closely meets the original FFG-7 design constraints. Secondly, to identify the design elements which are most impacted, either beneficially or adversely, by a shift to a superconducting propulsion system.

The output of the ship synthesis model will be specific data relating to gross characteristics, sustained speed, and endurance. The comparative analysis of the remaining six areas will be primarily subjective, but supported wherever possible with historical data, generally accepted design practice, and the authors personal experience and knowlegde.

5.2 Description of the Ship Synthesis Model

The ship synthesis model provides a method of estimating the weight, volume, electrical load, speed, and overall ship characteristics of feasible naval surface displacement ships. This computer program has been verified to give accurate results for monohull ships which range in size from 300 to 700 feet in length and from 1,700 to 17,000 tons displacement. The model does not attempt to define or check the arrangements required for the ship; therefore, highly arrangement dependent calculations cannot be performed using this model. These include damage stability, topside arrangement, internal arrangements, longitudinal balance, and strength calculations.

The synthesis model does provide solutions that satisfy

the following requirements. First, there must be a balance between the weight and the displacement. Secondly, internal space available must be equal to or greater than the internal space required. Thirdly, the energy available must at least meet the energy required to provide the ship's electrical demands and to propel the ship at the required speed. Finally, the distribution of weight and volume must be such as to satisfy the design criteria for transverse stability, girder strength, and seakeeping.

The model synthesizes a naval surface ship from the following relationships:

(1) Selecting starting estimates for full load displacement and center of gravity based on a set of relationships and rules.

(2) Selecting the proper geometric relationships for naval surface ships to match the hull form to the displacement and center of gravity.

(3) Linear fit for the selected hull form to the resistance and powering curves.

(4) Calculating the weight of the specified payload items and other ship equipment to determine a more exact value for full load displacement.

(5) Calculate the center of gravity based on specified ship configurations and compare to the estimated center of gravity.

(6) Calculate the volume required and match this with

the calculated hull dimensions.

(7) Perform electrical load calculations.

(8) Compare equipment sizing relationships with the existing ship dimensions.

(9) Iterate through the above steps until all of the relationships agree within a specified tolerance or until the maximum number of iterations has been performed without obtaining viable solutions, in which case the ship as specified is declared infeasible.

This particular synthesis model will converge accurately to the final configuration as the input data is refined. The rate of convergence is a function of the degree of input specification which can be specified to any degree.

5.3 Comparative Analysis

Before proceeding with an in depth comparative analysis, it is important to clearly establish the strengths and weaknesses of the synthesis model to be used. A comparison of this model with the design models presently used by both the U.S. Navy and Coast Guard showed a good correlation. In particular, this synthesis model proved to be very accurate for the FFG-7 class ships. Most of the computed values agreed within a few percentage points of the actual values. A tacit assumption in using this model is that the results will be sufficiently valid for a good analysis.

The synthesis model that is used does not attempt to

optimize the design solution. The program is executed to determine a feasible ship design, but not necessarily the best design. Different runs can be made to determine the design sensitivity to various design parameters.

5.3.1 Comparison of Gross Characteristics

Four parameters which provide a good measure of a ships size are length, beam, draft, and full load displacement. In this analysis the length of all three candidates was fixed at 408 feet (LBP), the same as the FFG-7. This was done to reduce the variability of the designs and to force a solution similar to the FFG-7.

The calculated beam at the midships waterline of the three candidate ships is 42.01 feet, 41.57 feet, and 41.43 feet for ships #1, #2, and #3 respectively. This compares with a beam of 44 feet for the FFG-7. These results reflect a finer, more slender design. The finer line of these ships contributes to a reduced water plane area and a corresponding reduction in hull resistance. This reduction in wetted surface area is the major factor contributing to a slightly higher maximum sustained speed for all the candidate ships.

The computed draft of the three candidate ships was 15.61 feet for #1, 14.96 feet for #2, and 15.2 feet for ship #3. The full load displacement draft of the FFG-7 if 15.0 feet.

Two important ship characteristics impacted by changes in beam and draft are stability and seakeeping. The synthesis

model assures that the stability is acceptable but does not provide any specific information concerning seakeeping. The stability analysis of the candidate ships will be done by taking the combined effects of changing beam and draft into account. The following relationships are used to determine the impact on stability.[12,13]

(1) $GM = KB + BM - KG$

(2) $KB = T - 1/3 \times (T/2 + V/A)$ (Morrish's Formula)

where: T = draft
V = underwater volume
A = maximum section area

(3) $BM = \dfrac{(LBP)(B^3)(C_a)}{V}$

where: B = beam at midship waterline
V = underwater volume
$C_a = .0733\ C_P + .0026$

(4) $Area = (B)(LBP)(C_{WP})$

where: B = beam at midship waterline
C_{WP} = water plane coefficient
$= .425(C_P)(C_X) + .526$

(5) $Volume = (B)(T)(LBP)(C_P)(C_X)$

where: C_P = prismatic coefficient
$= .59$ for all candidates
C_X = block coefficient
$= .75$ for all candidates

Applying the above relationships using the values generated by the synthesis model yields the following results.

SHIP #	KB	BM	KG	GM	GM/B
1	10.36	11.49	18.05	3.8	.090
2	9.93	11.74	17.93	3.74	.089
3	10.09	11.48	17.82	3.75	.090
FFG-7	11.0	10.91	18.44	3.47	.078

The actual value of GM and in particular the ratio of GM/B are good indicators of the stability of the various ships. In all three cases there is an improvement in GM and an increase in the ratio GM/B compared to the FFG-7. This implies that the stability of all three candidates will be better than the baseline design.

The impact of increasing GM in the candidate ships is also important in comparing roll periods of the various designs. A good approximation for roll period for destroyer type ships is:

$$\text{roll period in seconds} = \frac{.44\ B}{(GM)^{\frac{1}{2}}}$$

Applying this relationship to the candidate designs results in a roll period of 9.4 seconds for all three ships. This compares with a roll period of 10.4 seconds for the FFG-7. A reasonable roll period is in the range of 8 to 12 seconds. Hence, all four ships fall within acceptable design ranges.

The following generalizations can be made concerning the impact on seakeeping due to an increase in draft.

(a) permits better propeller immersion

(b) permits larger, more efficient propeller

(c) promotes better handling in heavy winds

(d) promotes directional stability

(e) requires and permits a larger rudder

(f) reduces the probability of slamming

(g) increases sea speed if ship is slamming limited

All of the candidate ships have drafts equal to or greater than the FFG-7 and hence, the seakeeping and stability characteristics of these proposed designs will be as good as or slightly better than the baseline ship. The addition of fin stabilizers would further enhance these characteristics. Fin stabilizers were slated for installation in the FFG-7 but were cancelled in order to keep the displacement and cost down. The fin stabilizers require a 30 ton weight penalty.

The fourth major characteristic to be considered is the full load displacement. As seen from table 5.1, all three candidates reflect a considerable reduction in displacement.

SHIP #	LIGHT SHIP	FULL LOAD	FULL LOAD NET CHANGE
FFG-7	2708	3617	----
1	2583	3430	-187
2	2400	3252	-365
3	2439	3294	-322

COMPARATIVE DISPLACEMENT(tons)

Table 5.1

The decreased displacement for candidate #1 is primarily due to a reduction in weight groups 1 and 2 and a reduction in the variable loads. This ship is physically smaller than the baseline because of the reduced beam. Hence, this design requires less structural steel, less shell plating, and less deck material than the FFG-7. The smaller hull of candidate #1 accounts for a 36 ton, 3% reduction in group 1 weight. The 87 ton, 31% reduction in group 2 weight is primarily due to the elimination of the reduction gear and the replacement of the CRP. The variable load reduction of 62 tons, 8%, is attributed to reduced endurance fuel requirements (54 tons) and reduced lube oil requirements (8 tons). This candidate exceeds the target displacement of 3,400 tons by 30 tons.

The large reduction in full load displacement of ship #2 is due to the reduction in weight groups 1, 2, and 3 and to a reduction in the variable loads. This design is also physically smaller than the baseline and, like ship #1, requires less structural steel. The additional reduction in group 1 weight is due to the elimination of the diesel generator foundations. The group 1 weight for this design is 91 tons, 8% less than the baseline group 1 weight. The 89 ton, 32% reduction in group 2 weight is primarily due to the elimination of the reduction gear and the replacement of the CRP. There is a significant 118 ton, 61% decrease in group 3 weight due to the elimination of the diesel engines, diesel engine ancillaries, and diesel fuel and cooling water piping systems. Reduced fuel

and lube oil requirements account for a 56 ton, 7% reduction in the variable loads. This design is 148 tons under the 3,400 ton target displacement.

Candidate #3 is simply a twin screw adaptation of candidate #2. The notable, 31 ton increase in group 2 weight is due to the additional shafting and propeller. There is also a 3 ton increase in the endurance fuel required over candidate #2. This design is 106 tons under the 3,400 ton target displacement.

5.3.2 Comparison of Maximum Sustained Speed

The maximum sustained speed for all three candidates showed an improvement of between 1 and 1.5 knots over the FFG-7. The factors contributing to the increase are as follows:

(1) A reduction in the wetted surface area with a corresponding reduction in hull resistance.

(2) Improved efficiency of the fixed pitch propeller over the CRP.

(3) A small increase in the installed horsepower.

The 3% improvement in propeller efficiency contributes to an increase in the overall propulsive coefficient(PC). For a specified value of effective horsepower, an increase in PC will increase the value of shaft horsepower since SHP = (EHP)(PC). The three proposed designs each have 230 more installed horsepower than the FFG-7. The impact of the increased horsepower is much less significant than the impact due to the reduction in wetted surface area. Shaft horsepower varies as the cube

of the speed and significant increases in speed require large increases in power in the high speed regimes.

5.3.3 Comparison of Endurance Fuel Requirements

The actual fuel load for the FFG-7 and the candidate fuel loads computed by the synthesis model are listed in table 5.2.

SHIP #	ENDURANCE SHP	FUEL(tons)	NET CHANGE(tons)
FFG-7	7,400	599	---
1	6,666	545	-54
2	6,454	553	-46
3	6,485	556	-43

ENDURANCE FUEL REQUIREMENTS

Table 5.2

Propulsion fuel weight is computed as follows:

$$W_{PF} = (\text{Endur})(\text{SHPE})(1.1)(\text{SFCAED})(1.1)/(V_{END})(2240)$$

where Endur = Endurance in NM

SHPE = Endurance SHP

1.1 = Tail pipe and Structural allowance

SFCAED = Specific Fuel Consumption at SHPE

1.1 = Hull Fouling Allowance

V_{END} = Endurance Speed in Knots

2240 = Conversion Factor from Lbs to Tons

Electrical generating fuel weight is computed as follows:

W_{EF} = (Endur)(KW24AV)(1.341)(1.1)(SFC24)/(V_{END})(2240)

where Endur = Endurance in NM

KW24AV = 24 Hour Average Electrical Load in KW

1.341 = Conversion Factor from KW to HP

1.1 = Tail Pipe and Structiral Allowance

SFC24 = Specific Fuel Consumption at the KW24AV Power Level

V_{END} = Endurance Speed in Knots

2240 = Conversion Factor from Lbs to Tons

Total Fuel = W_{PF} + W_{EF}

The various electrical loads conditions for the four ships are shown in table 5.3 below.

SHIP #	CRUISE(KW)	BATTLE(KW)	24 HOUR AVG(KW)
FFG-7	2400	1800	1300
1	2172	1720	1262
2	2113	1663	1208
3	2126	1672	1219

COMPARATIVE ELECTRICAL LOADS

Table 5.3

The reduction in propulsion fuel requirements for the three candidates can be attributed to a lower endurance SHP. Endurance SHP is calculated by the synthesis model using Taylor Standard Series estimations. This reduction in SHPE can be attributed to (1) a reduction is wetted surface area and (2) improved propeller efficiency. Propeller efficiency was an input to the synthesis model and was used in the calculation of the propulsive coefficient. SFCAED was taken as .57 lbs/HP-HR for all ships at the endurance power level.

The propulsion/electrical fuel breakdown for each of the four ships is shown in table 5.4 below.

SHIP	PROPULSION FUEL(tons)	ELECTRICAL FUEL	TOTAL	%CHANGE
FFG-7	513	86	599	---
1	462	84	546	-9
2	447	102	549	-9
3	449	103	552	-9

FUEL BREAKDOWN SCHEDULE

Table 5.4

Integrated electrical systems typically show improved fuel economy over non-integrated systems. This is not the case here, however, for the two electrically integrated designs being considered in this thesis. Improved fuel economy occurs only if the SFC of the integrated prime mover is lower than the SFC of the non-integrated electrical generating prime

mover. The SFC of the LM 2500 at the 24 hour average KW level is .57. The SFC for the diesel engines at the same power level is .45. However, the integration did contribute to the overall reduction in required fuel by accounting for a 118 ton reduction in weight and a 20,000 ft^3 reduction in requires volume. The impact on volume considerations will be discussed next.

5.3.4 Comparison of General Arrangements

The actual volumes of the FFG-7 and the candidate ship volumes computed by the synthesis model are shown in table 5.5 below.

SHIP	INTERNAL(ft^3)	SUPERSTRUCTURE(ft^3)	TOTAL
FFG-7	409132	82118	491250
1	374662	110705	485367
2	353662	110705	464367
3	357223	110705	467928

COMPARATIVE VOLUMES

Table 5.5

Table 5.5 shows a 5,883 ft^3, 1.2% reduction in total volume for ship #1. This reduction is attributed to the following:

(a) 400 ft^3 for CRP ancillaries and control

(b) 3070 ft^3 for removal of reduction gear

(c) 2450 ft^3 for fuel removal

(d) 200 ft^3 for removal of shafting and bearings

(e) 250 ft^3 for removal of lube oil

The additional required volume for the superconducting propulsion components is approximately 500 ft^3.

Table 5.5 shows an additional 21,000 ft^3, 5.5% reduction in required volume for ship #2. The major contributors to this additional reduction are as follows:

(a) 12,800 ft^3 for diesel generator removal

(b) 5,800 ft^3 for diesel auxillary equipment removal

(c) 2,000 ft^3 for diesel intake and exhaust duct removal

(d) 175 ft^3 for diesel lube oil removal

(e) 300 ft^3 for fuel filling and transfer piping, control panels, and operating stations.

The addition of the two ships service electrical generators requires an addition of approximately 75 ft^3.

Ship #3 is essentially identical to #2 except for the additional propulsion motor, shafting, breaking resistors, cryogenic piping, and fuel oil. Ship #3 shows a 23,332 ft^3, 4.8% reduction in total required volume compared to the FFG-7.

Candidate #2 reflects the largest reduction in required volume, 26,883 ft^3. If the decision were made to enlarge this design to the same hull dimensions as the FFG-7, then there would be approximately 20,000 ft^3 excess volume which could be assigned to additional equipment or functions. A similar statement can be made about ship #3. Candidate #1 shows

little promise of providing much excess volume since the required volume is only 5,800 ft^3 less than the baseline ship. However, ship #1 would provide for better arrangement flexibility of the machinery spaces.

Four areas of interest are affected by the excess volume afforded by the two superconducting, integrated designs. First, the fin stabilizers can now be added without sacrificing space presently assigned to other functions. These designs can absorb the 30 ton weight penalty for the fins and still remain below a full load displacement of 3,400 tons.

Secondly, the excess volume could be devoted to additional magazine space or other payload considerations. The impact on payload will be discussed in further detail in the following subchapter.

Thirdly, the additional space makes it possible to relocate potentially vulnerable spaces like CIC and Weapons Control Centers. Several critical control spaces on the FFG-7 are presently located high in the superstructure because of insufficient hull arrangement space. These and other vulnerability/survivibility considerations will be discussed in a later subchapter.

Lastly, there is a real possibility of having to increase the present manning level on the baseline ship. The additional required living spaces could be alloted without infringing on spaces already designated for other functions or reducing the habitability standards the FFG-7 presently enjoys.

In general, the superconducting impact is primarily on arrangement flexibility. The real gain in arrangement space is due to the electrical integration.

5.3.5 Payload Comparison

The installed armament of the three candidate ships is identical in all respects to the FFG-7. This was done to ensure that all the ships had the same firepower and capability. The controlling design variables for payload in the FFG-7 are topside space, weight, and total volume. All three candidates contribute in differing degrees to allowing for additional weight and/or providing for additional volume. However, none of the proposed designs show any potential for increased topside space. This is primarily due to having constrained the LBP to 408 feet. Superstructure volume is usually a function of ship length.

Ship #1 cannot accept any additional payload without further exceeding the 3,400 ton full load displacement target. Candidates #2 and #3 can accept 148 tons and 106 tons of additional weight respectively without exceeding the target displacement. The excess volume in these two designs has already been established at approximately 20,000 ft^3.

Since none of the proposed designs offer any additional topside space, the addition of gun mounts, missile launchers, or torpedo tubes is not a consideration. The most likely consideration would be increasing the number of missiles and/or torpedoes or the amount of gun ammunition. Designs #2 and #3 could accommodate a 100% increase in gun ammunition (wt. gp. 803).

This would amount to an additional weight of 41.8 tons and a volume of 4,500 ft^3. A 100% increase in the number of missiles would require 8,800 ft^3 of volume and an increase in displacement of 63 tons. A 100% increase in the torpedo load would require 3,500 ft^3 of volume and a 14 ton increase in weight.

A 100% increase in the number of missiles, torpedoes, and ammunition would require a volume of 16,800 ft^3 and result in an increase in full load displacement of 118 tons. Candidate #2 has both the weight margin and the excess volume to accomodate an increase of this magnitude without exceeding the target displacement. Candidate #3 could absorb only a 90% increase or any combination of the options which adds up to a total of 106 tons or less.

The important point resulting from the above discussion is not so much the order of magnitude of the increases but that the superconducting/integrated designs offer an option that is not possible with the present FFG-7 design; a substantial increase in payload.

The risk associated with these proposed designs and how it might effect the fighting capability of the ship will be discussed in detail in subchapter 5.3.7.

5.3.6 Vulnerability/Survivability Comparison

Vulnerability: In the context of this discussion, vulnerability is defined as a measure of the likelihood of a ship sustaining damage. Hence, a highly vulnerable ship is one which has a high probability of being damaged, whether it is

due to attack, weather and sea conditions, or operational complexity.

Numerous parameters go into the determination of a ship's vulnerability. Some of the major parameters are as follows:

(1) The ship's noise level and acoustic signature

(2) The degree of complexity and degree of reliability of installed equipment

(3) The manuverability and response characteristics of the ship

(4) The extent and effectiveness of the ship's armor

(5) Location of vital equipment and control spaces

(6) The ship's infrared signature

(7) The ship's radar cross section

(8) Capabilities and limitations of the ship's defensive and offensive weapons

(9) The extent and effectiveness of equipment shock hardening

(10) The structural strength of the ship

The superconducting and superconducting/integrated designs would differ from the FFG-7 in only the first five of these parameters.

All of the candidates will have a reduced own ship's noise level. The three major contributors to this reduction are:

(1) The elimination of the reduction gear

(2) The elimination of the diesel engines (candidates #2 and #3)

(3) The elimination of the CRP and its control system. Reduction gears and diesel engines emit low frequency vibrations which are detectable by sophisticated sonars at long ranges. The CRP noise level is considerably higher than a fixed pitch propeller because of the CRP hydraulic system.

It is difficult to compare the degree of complexity and reliability of the various designs. All of the ships are complex engineering achievements. Two of the factors contributing to this complexity are the level of sophistication and the degree of automation. All of the candidate will have a level of sophistication and automation equal to or greater than that of the baseline ship. Hence, none of the proposed designs will offer any relief in the complexity of the ship.

The reliability of the superconducting components has yet to be determined. Historically, electric motors and generators have proven to be extremely reliable and trouble free. It is safe to assume that if these devices cannot be designed with an acceptable level of reliability, they simply can not be considered as viable alternatives.

One very important consideration of the superconducting motors and generators used in these proposed propulsion plants is that of repairability. The construction and design of these devices is such that they are essentially not repairable underway. If a casualty occurs to a superconducting motor or generator, it is essentially lost until return to a repair

facility and replacement can be accomplished. Hence, in order for these devices to be viable they must be as reliable as the shaft, propeller, and reduction gears which also fall into this non-repairable underway catagory. The overall system reliability can be enhanced by incorporating sufficient redundency and casualty control as is done with the cryogenic refrigeration system.

It is important to compare the reliabilities of the integrated and non-integrated electrical systems. The FFG-7 has four sources of ships service electrical power, two of which are needed to sustain the ships battle load. Candidates #2 and #3 each have two sources of ships service electrical power, one of which will sustain the battle load.

If reliability is defined as the probability that a unit will perform its intended function for a specified period of time, then reliability can be quantified as:[14]

$$R = 1 - \frac{MTTR}{MTBF}$$

where R = reliability

MTTR = mean time to repair

MTBF = mean time between failures

Presently accepted values for mean time to repair and mean time between failures for Navy propulsion systems and the computed values for reliability are shown in table 5.6.

COMPONENT	MTTR(hrs)	MTBF(hrs)	R
LM 2500 Gas Turbine	24	4000	.9940
AC Generator	6	5000	.9988
Diesel Engine	8	3000	.9970

ELECTRICAL SYSTEM RELIABILITY VALUES(14)

Table 5.6

The reliability of two components in series is equal to the product of their individual reliabilities. Therefore, the reliability of the LM 2500/AC Generator is .9928 and the diesel generator reliability is .9958. Hence, the probability that the integrated system can maintain battle load is .999481 and the probability that the non-integrated system can maintain battle load is .999999. There is, then, a measurable but not significant difference in the reliabilities of the two systems. The slight improvement in reliability of the non-integrated system is due to its redundancy. The cost of this redundancy is a substantial weight and volume penalty. It should be noted, however, that both the integrated and non-integrated systems meet the original FFG-7 design requirement of being able to maintain the ship battle load with one ships service electrical generator inoperative.

The twin screw design, candidate #3, offers an opportunity to improve the overall propulsion system reliability. There are some in the design community who believe that this

increase in reliability is not worth the additional weight and volume penalty. Support for their position can be found in a variety of experiments and studies that show that if an underwater explosion is sufficiently close to cause damage to one screw then there is a high probability that both will be lost. Secondly, they claim that there is little difference in the performance of a single screw ship and a twin screw ship in the open ocean at cruise speeds. The other school of thought is that the improved manuverability offered by twin screw designs at slow speeds is an important consideration. Operational experience shows that the twin screw ships are considerably easier to get underway and easier to navigate in restricted waters. This improved manuverability is also significant during unrep operations where ships are required to operate at very close distances. An additional and very important consideration is that a twin screw design offers greater assurance against the complete loss of propulsion due to personnel errors that cause casualties to shaft components or acts of God which effect propellers.

Irregardless of which school of thought one supports, the important consideration here is that the superconducting/integrated design offers an option which was not possible with the conventional type propulsion system utilized in the FFG-7. In the case of the FFG-7, this option could be exercised without increasing the hull size or displacement.

There is little in the published literature that suggests

that the superconducting/fixed pitch propeller configuration enjoys any significant advantage in response time over the CRP design. The CRP design does have to provide for unloading the prime mover during transition through zero pitch to guard against overspeeding the turbine. This function is not necessary with the electric drive since dynamic braking resistors can absorb the transient currents. Experience with electric drive shows that these systems provide for more accurate control of propeller RPM.

At present, the FFG-7 does not have any protective armor aside from its shell plating. There are plans to backfit the vital areas such as magazines and critical control spaces with a new, light weight synthetic armoring material. This will, of course, increase the group 1 weight of the FFG-7 and, hence, aggravate its already overweight condition. Candidates #2 and #3 could both accept in excess of 100 tons of armor and still remain below the target displacement.

The question of equipment and control space location is an on going debate between designers and operators. Critical equipments and spaces can best be protected when places within the hull. Operators claim that they can best fight the ship when the Combat Information Center(CIC) is located near the bridge. The CIC, communications center, radar rooms, torpedo magazine, and gun magazine on the FFG-7 are all located above the main deck. Some of these areas were located there for operational considerations and some because of insufficient

hull volume. The only two solutions to this situation are (1) enlarge the hull to accomodate more volume or (2) to make better use of existing hull volume. For a ship with the FFG-7 hull dimensions, candidates #2 and #3 provide an additional 20,000 ft^3 of arrangement space below the main deck level. These designs offer the opportunity to provide greater protection for critical spaces without enlarging the FFG-7 hull or increasing its displacement.

Survivability: For the following discussion, survivability will be defined as the the ability of a ship to carry out all or part of its assigned mission after incurring damage. Two major factors determine the ships survivability. First, the design and construction of the ship and secondly, the level of competence of the crew. Naval architectural considerations have little effect on the latter. A well designed and constructed ship may be lost due to poor crew response and a well trained crew may not be able to save a poor design. Hence, this discussion will center on the design considerations which contribute to good survivability.

Fire and flooding are the two worst casualties that can threaten a ship, with fire being the most difficult to combat and the most difficult to design for. There are design specifications, like floodable length criteria, which assist the designer in determining the ships compartmentation and, hence, provide some protection at the design level for flooding control. There are no such design aids for fire protection. In

addition, the designer has a good deal of control in establishing the ships intact and damage stability.

Within certain limitations, designers are free to choose the location and degree of redundency of critical components such as propulsion and electrical generating equipment. The choice of where to locate the propulsion components in a conventional propulsion system is severely limited by the requirement to have all the propulsion components "in line" with the shaft. Hence, in designs like the FFG-7 these critical components are all grouped together in a single engine room. Electric propulsion offers the distinct advantage of being able to separate critical propulsion components and increase the probability of maintaining propulsion. For a frigate design, the twin screw, electric propulsion system offers the highest level of survivability since the loss of a single shaft or propeller will not totally disable the ship.

The ability to maintain ships service electrical power is even more important than maintaining propulsion and tantamount to the survival of the ship. A ship may be able to continue fighting without propulsion but it is totally impotent as a weapons platform without electrical power. The FFG-7 designers took considerable care to ensure that the electrical generating capability of the ship could be maintained by suitably separating the four diesel generators. This separation, coupled with redundency, provides a high level of confidence in the FFG-7 ships service electrical system. This same level

of confidence is not enjoyed by the integrated designs. There are only two ship service electric generators incorporated in these designs and each is slaved to a propulsion prime mover. As a result, the loss of a prime mover not only degrades the propulsion system but the electrical system as well. The loss of both prime movers totally disables the propulsion and electrical system.

5.3.7 Risk Analysis

In essence, there is little analysis needed to compare the relative risks of the FFG-7 and the proposed candidates. A major design element of the FFG-7 design philosophy was low risk. This was reflected directly in the design constraints by requiring that the FFG-7 use only operationally proven, standardized equipments. The only risk associated with the FFG-7 is the level of automation required to facilitate operation of the ship with a small crew.

On the other hand, the proposed designs present the extremely high level of risk inherent in any new, unconventional design. The Navy has no operational experience with extremely high electric currents associated with the superconducting machines. The same is true of shipboard cryogenic systems. High electric currents and liquid helium are obviously potential hazzards to the crew.

The Navy's present acquisition policy of "fly before buy" will go a long way in ensuring that the systems will function effectively and safely. There appears to be little doubt in

the minds of the researchers that these systems are feasible and workable. However, prolonged testing under actual operating conditions is the only way to determine the systems performance and acceptability. Therein lies the risk. Considerable funding and effort will be required to take one of these designs that far along. This situation is not unlike the Surface Effect Ship (SES) and hydrofoil program.

Even if these superconducting propulsion systems can be built to operate at their advertised characteristics, the Navy will have to address the question of the desirability of having maintenance free, non-repairable critical equipments onboard combatant ships.

5.3.8 Maintenance Analysis

There is a trend in the Navy toward reducing onboard maintenance in favor of increased support by shore and tender facilities. Such a concept was incorporated into the FFG-7, necessitated, at least in part, by the reduced manning level. This concept leads to an increased use of modularity and computer assisted troubleshooting and repair. Gas turbines are, as a rule, not overhauled onboard but simply removed and replaced. The same would be true of the superconducting motors and generators.

A major point of contention with the superconducting machines is that they could not be repaired underway, even in an emergency. This doesn't present an entirely new problem since there are components in conventional propulsion systems

that fall into the same catagory; shafts, reduction gears, and propellers for example. It seems essential, then, that the superconducting components be designed and constructed so as to have a MTBF at least as high as the shaft components', 200,000 hours.

The electrical integration will reduce onboard maintenance requirements. Diesel engines have proven to be quite reliable, but must be coupled with an intensive preventative maintenance program. Our experience with diesel electric submarines shows that more manhours are expended on diesel engine maintenance and repair than any other piece of equipment. It would seem that the elimination of diesel engine maintenance would be a welcome relief to a reduced manning ship like the FFG-7.

The dollar value of this reduction will be addressed in detail in the following subchapter.

5.3.9 Cost Analysis

At this time it would be very difficult to put a price on the acquisition and installation of a superconducting propulsion system. Without this data it would be equally difficult to determine a meaningful acquisition cost of a new frigate utilizing superconducting propulsion. This thesis will cover an economic comparison of how much a superconducting propulsion system could cost and be considered economically feasible.

The cost of removing the mechanically driven propulsion machinery and the giesel generators will be computed. If these equipments had not been installed, then the cost of removal

can be considered a savings This value will be added to any operating and maintenance savings and the result will be considered as the economically feasible cost of a superconducting propulsion system. The operating costs will be based on a 20 year life cycle.

The major components removed from the baseline ship are the shaft, bearings, propeller, reduction gear, and for ships #2 and #3, the diesel generator sets and diesel support systems. Table 5.7 lists the associated equipment removal costs. These costs represent the average cost of removal at various ship yards and repair facilities in 1977 dollars. The 1979 cost was computed based on an inflation rate of 8% per year.

ITEM	WEIGHT	RATE	COST(1977)	COST(1979)
Shaft/Bearings	49.85	$2000/ton	$99,700	$116,290
Propeller	31.75	$2000/ton	$63,500	$71,066
Reduction Gear	----	$20/SHP	$800,000	$933,120
Diesel Generators	59.46	$2000/ton	$118,920	$138,707
Diesel Support	37.08	$2000/ton	$74,160	$86,500
Diesel Ducting	2.0	$1000/ton	$2,000	$2,322

MACHINERY REMOVAL COSTS[14,15]

Table 5.7

The removal of these equipments results in a cost of $1,209,308. If the diesel generators, ducting, and support

equipment are not removed, the cost is only $981,769.

Propulsion plant operating costs will be based on a 30% underway time per year. This amounts to 109 days and is representative of a frigate class ship. The analysis will assume that 94% of the underway time is spent at endurance speed and that the remaining 6% is spent at full power. Underway fuel consumption will be calculated using a SFC of .57 lbs/hp-hr for the LM 2500 at endurance and .39 lbs/hp-hr at full power. Diesel engine SFC is assumed to be .45 lbs/hp-hr at the 24 hour electrical load power level. The price of fuel is assumed to be $17 per barrel. Manning costs will be considered equal for all ships and not included in the calculations. The required computational inputs will be taken from the synthesis model results.

Propulsion fuel consumption per year at full power is calculated as follows:

$$F_{PFP} = \frac{(SFCFP)(DUW)(24)(.06)(SHPFP)(7.23)}{2240}$$

where SFCFP = specific fuel consumption at full power

DUW = # days underway per year = 109

24 = 24 hours/day (conversion factor)

.06 = 6 percent underway time at full power

SHPFP = shaft horsepower at full power

7.23 = 7.23 barrels/ton (conversion factor)

2240 = 2240 lbs/ton (conversion factor)

Propulsion fuel consumption per year at endurance is calculated as follows:

$$F_{PE} = \frac{(SFCE)(DUW)(24)(.94)(SHPE)(7.23)}{2240}$$

where SFCE = specific fuel consumption at endurance

DUW = # days underway per year = 109

24 = 24 hours/day (conversion factor)

.94 = 94 % underway time at endurance

SHPE = shaft horsepower at endurance

7.23 = 7.23 barrels/ton (conversion factor)

2240 = 2240 lbs/ton (conversion factor)

Electrical generating fuel consumption per year at the 24 hour average KW load is calculated as follows:

$$F_{E} = \frac{(SFC24)(DUW)(24)(KW24AV)(1.341)(7.23)}{2240}$$

where SFC24 = specific fuel consumption at the 24 hour average KW power level

DUW = days underway = 109

24 = 24 hours/day (conversion factor)

KW24AV = 24 hour average KW load

1.341 = 1.341 HP/KW (conversion factor)

7.23 = 7.23 barrels/year (conversion factor)

2240 = 2240 lbs/ton (conversion factor)

Total tons of fuel consumed per year = $F_{PFP} + F_{PE} + F_{E}$

Table 5.8 below summarizes the results obtained by applying the previously defined formulas. The fuel values are expressed in barrels per year and the cost is based on the assumed cost of $17 per barrel.

SHIP	FULL POWER	ENDURANCE	ELECTRICAL	TOTAL	COST
FFG-7	7,903	33,478	6,623	48,004	$816,068
1	7,948	30,157	6,430	44,535	$757,095
2	7,948	29,198	7,796	44,942	$764,014
3	7,948	29,338	7,867	45,153	$767,601

ANNUAL FUEL COST SUMMARY

Table 5.8

Candidates #2 and #3 will realize an additional savings in diesel engine maintenance and repair costs. The empirical relation used to determine this cost is as follows:(14)

$$\text{Cost} = (9.4)(\text{SHP}/1000) + 4875(\text{SHP}/1000)^{2/3}$$

$$= (9.4)(1500/1000) + 4875(1500/1000)^{2/3}$$

$$= \$7{,}934 \text{ per diesel per year}$$

$$= \$31{,}700 \text{ per four diesels per year}$$

Table 5.9 summarizes the annual operating cost savings for the three candidate ships.

SHIP	FUEL COST	DIESEL M&R COST	SAVINGS OVER FFG-7
FFG-7	$816,068	$31,700	-----
1	$757,095	$31,700	+ $58,973
2	$764,014	-----	+ $83,754
3	$767,601	-----	+ $80,167

ANNUAL OPERATING COST SUMMARY

Table 5.9

The present value (PV) of the operating cost savings will be computed with an assumed discount rate of 6%. The discount rate factor (C_{DR}) is computed as follows:(14)

$$C_{DR} = \frac{(1 + DR)^{L} - 1}{DR(1 + DR)^{L}}$$

where DR = discount rate

L = life cycle of ship in years (20)

$C_{DR} = 11.46$

The present value is calculated as follows:(14)

$$PV = (\text{cost/year})(C_{DR})$$

The present value of the annual operating cost savings for the three candidate ships are as follows:

PV #1 = ($58,973)(11.46) = $675,830

PV #2 = ($83,754)(11.46) = $959,820

PV #3 = ($80,167)(11.46) = $918,713

The total savings due to not having to remove the propulsion equipment and the present value of the operating cost savings are summarized in table 5.10 below.

SHIP	EQUIPMENT REMOVAL	OPERATING COST(PV)	TOTAL
#1	$981,769	$675,830	$1,657,599
#2	$1,209,308	$959,820	$2,169,128
#3	$1,209,308	$918,713	$2,128,021

CANDIDATE SHIP COST SUMMARY

Table 5.10

The totals shown in table 5.10 represent a realistic lower bounds since all of the parameters used in the calculations are lower limits and hence, conservative. The price of fuel will most certainly rise over the next 20 years as will the maintenance and repair costs. In addition, the life cycle of the ship will likely exceed 20 years.

Using the calculated values in table 5.10 as a guideline, the superconducting propulsion machinery is considered economically feasible if the acquisition cost of the required components is less than 2.1 million dollars for candidates #2 and #3 and less than 1.7 million dollars for candidate #1. Extremely tentative estimates place the cost of the superconducting components at between 2 and 3 million dollars.(16) If these preliminary estimates are anywhere near accurate, then

the superconducting propulsion plants are economically feasible, particularly in light of the conservative nature of the cost calculations.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

The results of the analysis indicate that the FFG-7 could have been designed and built to the original design requirements and constraints if a superconducting, electrically integrated propulsion system had been available. An FFG-7 design utilizing a superconducting propulsion system without electrical integration would have exceeded the design displacement constraint by approximately 30 tons. However, this design would still represent an impressive 187 ton reduction over the non-superconducting design.

The ability to produce these designs is primarily due to the significant reductions in weight and required volume. All three candidate designs have seakeeping and stability characteristics equal to or better than the baseline ship. In addition, the electrically integrated designs have sufficient weight and volume margins to facilitate an impressive increase in payload. Candidate #3 offers a twin screw option which can now be considered practical.

The most dramatic impact centers on the integrated ships service electrical system. The results of this analysis clearly support earlier conjectures and studies about the possibility of significant gains afforded with integrated systems. The propulsion system presently used in the FFG-7 is not conducive to an integrated system because of the transient behavior of the

gas turbine; particularly during shaft reversals. The electric propulsion systems proposed in this thesis offer stable, constant speed prime mover output which is needed to generate constant frequency electrical power. The utilization of one of these electrically integrated systems necessitates the acceptance of the high level of risk inherent in the design.

The work associated with this thesis leads to the following specific conclusions.

(1) An 89 ton, 31% reduction in propulsion machinery weight, exclusive of fuel, can be realized by the substitution of a superconducting propulsion system for the presently installed system.

(2) A 118 ton, 61% reduction in electrical machinery weight can be realized by utilizing an integrated ship service electrical system.

(3) A 26,800 ft^3, 6% reduction in total required volume can be realized by substitution of a superconducting/electrically integrated system for the presently installed system.

(4) A 365 ton, 10% reduction in full load displacement can be realized with the superconducting/integrated system.

(5) A 46 ton, 8% reduction in required fuel is possible with the superconducting/electrically integrated system.

(6) A 2 knot, 7% increase in maximum sustained speed can be realized with the superconducting/electrically integrated system.

(7) A superconducting/electrically integrated propulsion system is considered economically feasible if the acquisition cost is less than approximately 2.1 million dollars.

(8) A non-integrated/superconducting propulsion design will exceed the desired displacement of 3,400 tons by approximately 30 tons, less than 1%.

The following general conclusions can be made.

(1) The primary naval architectural impact of the superconducting propulsion system is in the area of arrangement flexibility. These systems offer a lighter propulsion system and a corresponding reduction in displacement over other alternatives. These systems also provide the mechanism for allowing the utilization of an integrated ship service electrical system.

(2) The primary naval architectural impact of the electrical integration is in the area of reduced weight and volume requirements.

(3) The primary operational impacts of superconducting/electrically integrated systems are in the areas of reduced noise, reduced maintenance costs, and reduced operating costs.

(4) The major drawback of the superconducting/electrically integrated system is the high level of risk inherent in these designs. The risk is primarily attributed to the uncertainity of the performance of the machines, the reduction in system reliability due to the reduction in redundency, and the potential hazzards to the crew due to high electric currents and liquid helium.

(5) The superconducting/electrically integrated systems offer considerable potential for improved designs. The major considerations are in the areas of increased payload, improved seakeeping and stability, and improved vulnerability/survivability.

This thesis has touched on several areas which require further investigation. The most important of these is the actual design and construction of the superconducting devices. In addition, further investigation and development of the cryogenic refrigeration systems is needed. The hazzards associated with the high electric currents and liquid helium must also be explored and minimized.

All of the superconducting propulsion studies, both published and unpublished, with which the author is familar, have dealt with applications to destroyer type, volume limited designs. There seems to be some preliminary support to the idea that the benefits gained are proportional to the size of the system; the larger the system, the more impressive the

gains. Verification of this hypothesis could be achieved by conducting an analysis, similar to the one done in this thesis, on a large, weight limited ship such as a CVA, LHA, or LPH. If the results are as anticipated, then a 30,000 ton displacement design could be redesigned with a displacement of 25,000 tons, a 17% reduction.

In the authors opinion, the most attractive design to be pursued is the twin screw, superconducting/electrically integrated design, candidate #3. A reasonable approach would be to take the present FFG-7 hull form, limit the full load displacement to 3,400 tons, and conduct a detailed tradeoff study to determine how best to utilize the excess weight and volume margins.

A viable propulsion system which couples gas turbine prime movers with electric propulsion motors opens the door for some innovative considerations. For example, the possibility of installing the gas turbines vertically could be investigated. If this could be accomplished, ducting runs could be minimized, efficiency could be improved, and more usable deck space could be realized. It might also be possible to locate the gas turbines in such a way that the exhaust gases could be ducted over the side and help reduce the ships infrared signature and reduce exhaust gas corrosion of masts and antennas. In addition, propulsion components could be located and positioned to facilitate easy removal and replacement.

There are two additional ideas not considered in this

thesis which warrent further investigation. First, the application of superconducting electric propulsion components with nuclear power plants. This might prove extremely useful for nuclear powered submarines. There is a continual push to reduce the noise level in submarines. The elimination of reduction gears and unnecessary shaft bearings would be very beneficial in reducing noise. Nuclear submarine propulsion systems are already designed to utilize electric propulsion in an emergency. In addition, the clutch mechanism could be eliminated and a smaller, more efficient propulsion turbine could be redesigned since there would be no need for an astern turbine.

The second consideration is a reevaluation of the use of combined propulsion systems. The utilization of superconducting electric motors negates the necessity of mechanically interfacing the different prime movers since there is no longer a requirement for reduction gears and exotic clutch mechanisms.

In this authors opinion, the potentially impressive gains afforded by superconducting propulsion systems warrent the considerable expenditure of reasources necessary to develop and implement them. I strongly recommend that the Navy continue its research and development efforts and that a superconducting/electrically integrated design be persued.

APPENDIX I

BSCI WEIGHT GROUPS - DETAILED LISTING

MODIFIED BSCI WEIGHT GROUPS

Sub Group	Description
Hull Structure---Group 1	
100	Shell Plating
101	Longitudinal & Transverse Framing
102	Inner Bottom Plating
103	Platforms & Flats
107	All Decks(BSCI 104 thru 110)
111	Superstructure
112	Propulsion Foundations
113	Foundations for Auxillaries & Other Equipments
114	Structural Bulkheads
115	Trunks & Enclosures
116	Structural Sponsons
117	Armor
118	Aircraft Saddle Tank Structure
119	Castings & Forgings
120	Sea Chests
121	Ballast & Buoyancy Units
122	Special Doors & Closures
123	Doors & Hatches(BSCI 123,124)
125	Masts & Kingposts
127	Sonar Domes
128	Towers & Platforms
150	Welding, Riveting, & Fastening

Sub Group	Description
151	Free Flooding Liquids

Propulsion---Group 2

200	Boilers & Energy Converters
201	Propulsion Units
202	Main Condensers & Air Ejectors
203	Shafting, Bearings, & Propellers
204	Combustion Air Supply
205	Uptakes & Smokepipes
206	Propulsion Control Equipment
207	Main Steam System
208	Feed Water & Condensate System
209	Circulating & Cooling Water System
210	Fuel Oil Service System
211	Lubricating Oil System
250	Propulsion Repair Parts
251	Propulsion Operating Fluids

Electric Plant---Group 3

300	Electric Power Generation
301	Power Distribution Switchboards
302	Power Distribution System(Cable)
303	Lighting System

Sub Group	Description
350	Electric Plant Repair Parts
351	Electric Plant Operating Fluids

Command & Control---Group 4

400	Navigation Equipment
401	Interior Communications Equipment
402	Gun Fire Control Systems
403	Countermeasures(non-electric)
404	Electronic Countermeasures
405	Missile Fire Control Systems
406	ASW & Torpedo Fire Control Systems
407	Torpedo Fire Control Systems (Submarines)
408	Radar Systems
409	Radio Communications Systems
410	Electronic Navigation Systems
411	Space Vehicle Electronic Tracking Systems
412	Sonar Systems
413	Electronic Tactical Data Systems
415	Electronic Test, Checkout, & Monitoring Equipment
450	Command & Control Repair Parts
451	Command & Control Operating Fluids

Sub Group	Description
Auxillary Systems---Group 5	
500	Heating System
501	Ventilation System
502	Air Conditioning System
503	Refrigeration Spaces, Plant, & Equipment
504	Gas, HEAF, All Liquid Cargo Piping, Aviation Lube Oil, & Sewage System
505	Plumbing System
506	Firemain, Flushing, Sprinkler, & Sea Water Service Systems
507	Fire Extinguishing System
508	Drainage, Ballast, Stabilizing Tank Systems
509	Fresh Water System
510	Scuppers & Deck Drains
511	Fuel & Diesel Oil Filling, Venting, Stowage, & Transfer Systems
512	Tank Heating System
513	Compressed Air System
514	Auxillary Steam, Exhaust Steam, Steam Drains
515	Buoyancy Control System (Submarines)
516	Miscellaneous Piping Systems
517	Distilling Plant
518	Steering System
519	Rudders

Sub Group	Description
520	Mooring, Towing, Anchor & Aircraft Handling, Deck Machinery
521	Elevators, Moving Stairways, & Stores Handling System
522	Operating Gear for Retracting & Elevating Units
523	Aircraft Elevators
524	Aircraft Arresting Gear, Barriers, & Barricades
525	Catapults & Jet Blast Deflectors
526	Hydrofoils
527	Diving Planes & Stabilizing Fins
528	Replenishment At Sea & Cargo Handling Systems
550	Auxillary System Repair Parts
551	Auxillary System Operating Fluids

Outfit & Furnishings---Group 6

600	Hull Fittings
601	Boats, Boat Stowage & Handling
602	Rigging & Canvas
603	Ladders & Gratings
604	Nonstructutal Bulkheads & Doors
605	Painting
606	Deck Covering
607	Hull Insulation
608	Storerooms, Stowages & Lockers

Sub Group	Description
609	Equipment for Utility Spaces
610	Equipment for Workshops, Labs, & Test Areas
611	Equipment for Galley, Scullery, Pantry, & Commissary
612	Furnishings for Living Spaces
613	Furnishings for Offices, Control Centers, & Machinery Spaces
614	Furnishings for Medical & Dental Spaces
615	Radiation Shielding
650	Outfit & Furnishings Repair Parts
651	Outfit & Furnishings Operating Fluids

Armament---Group 7

Sub Group	Description
700	Guns, Gun Mounts, Ammo Handling, Ammo Stowage(BSCI 700, 701, 702)
703	Special Weapons Handling & Stowage
704	Rocket & Missile Handling, Stowage, & Launching Systems (BSCI 704, 705, 706, 707)
708	Torpedo Tubes, Torpedo Handling & Stowage
710	Mine Handling & Stowage Systems
711	Small Arms & Pyrotechnic Stowage
712	Air Launched Weapons Handling & Stowage(BSCI 712, 713)
720	Cargo Munitions Handling & Stowage

Sub Group	Description
750	Armament Repair Parts
751	Armament Operating Fluids

Variable Loads---Group 8

800	Ships Officers, Crew, & Effects
801	Troops & Effects
802	Passengers & Effects
803	Ships Ammo
804	Aviation Ammo
805	Aircraft
806	Provisions & Personnel Stores
807	General Stores
808	Marines Stores
809	Aero Stores
810	Ordnance Stores(Ship)
811	Ordnance Stores(Aviation)
812	Potable Water
813	Reserve Feed Water
814	Lube Oil(Ship)
815	Lube Oil(Aviation)
816	Fuel Oil
817	Diesel Oil
818	Gasoline
819	JP-5
820	Miscellaneous Liquids

Sub Group	Description
821	Cargo
822	Ballast Water
825	Future Development Margin

APPENDIX II

FFG-7 BASELINE 3 DIGIT BSCI WEIGHTS

WEIGHT GROUP	WEIGHT(tons)	WEIGHT GROUP	WEIGHT(tons)
100	266.04	200	0.
101	130.24	201	108.68
102	0.	202	0.
103	61.63	203	81.6
107	352.74	204	1.89
111	30.37	205	20.15
112	43.81	206	20.15
113	94.13	207	0.
114	128.0	208	0.
115	34.39	209	4.75
116	0.	210	4.74
117	0.	211	20.94
118	0.	250	2.0
119	39.21	251	16.12
120	3.19	Group 2 Total	287.04
121	0.		
122	1.7	300	108.59
123	18.8	301	23.45
125	0.	302	33.86
127	0.82	303	17.84
128	7.1	350	2.48
150	18.11	351	9.5
151	18.27	Group 3 Total	195.72
Group 1 Total	1248.55		

WEIGHT GROUP	WEIGHT(tons)	WEIGHT GROUP	WEIGHT(tons)
400	3.96	506	41.30
401	12.34	507	16.89
402	4.99	508	16.74
403	10.44	509	17.14
404	5.63	510	.94
405	5.98	511	40.40
406	2.86	512	0.
407	0.	513	34.37
408	11.73	514	.87
409	14.95	515	0.
410	2.98	516	0.
411	0.	517	6.04
412	23.57	518	11.79
413	7.08	519	31.43
415	1.85	520	45.12
450	.79	521	8.25
451	6.98	522	.07
Group 4 Total	116.13	523	0.
		524	0.
500	11.58	525	0.
501	70.05	526	0.
502	26.37	527	0.
503	2.21	528	7.79
504	7.26	550	3.06
505	17.68	551	31.66

WEIGHT GROUP	WEIGHT (tons)	WEIGHT GROUP	WEIGHT (tons)
Group 5 Total	449.01	708	5.58
		710	0.
600	4.83	711	0.
601	12.09	712	.23
602	6.68	720	0.
603	42.53	750	4.57
604	24.77	751	1.04
605	18.11	Group 7 Total	93.54
606	24.32		
607	58.82	800	21.47
608	39.99	801	0.
609	6.69	802	0.
610	9.26	803	41.38
611	18.93	804	9.3
612	31.45	805	21.55
613	17.89	806	22.11
614	1.79	807	18.53
615	0.	808	0.
650	.63	809	0.
651	0.	810	0.
Group 6 Total	318.78	811	0.
		812	27.6
700	19.53	813	0.
703	0.	814	14.46
704	62.59	815	0.

WEIGHT GROUP	WEIGHT(tons)
816	599.58
817	0.
818	0.
819	63.81
820	0.
821	0.
822	0.
825	68.91
Group 8 Total	839.79

APPENDIX III

SYNTHESIS MODEL INPUT DATA FORMAT

The following is a complete listing of the data used as the input to the ship synthesis model. A complete description of the format can be found in appendix A of reference (12).

CANDIDATE #1

1 0 20 4500 408 0 0 .59 .75 0 0 6 40230 0 0 2 1

17 1 1 180 16.5 0 0 0 .67 .7

31 5 4 0 4 0 0 0 1000 0 0 .3 0 0 0 2 1 0 0 17 15 153

56 45 0 0 0 0 1 2 0 .08 0 10 20 .1 20 .05 0 2 1 0 2

100 1 2 1 24 1 27 1 41 1 48 1 61 8 64 1 65 1 75 1 100

120 1 102 1 116 800 119 10000 124 1 131 40 168 2 180

134 1 185 1 190 6 200 1 204 1 208 1 209 1 212 1 213 1 214

152 4 215 193 217 10 219 1 221 12 226 1 230 1 232 1 242

307 320

311 30.37 38.1 94.13

315 34.94 .001

317 .001 .001 39.21 3.19 .001 1.7 18.8

325 .001

327 .82 7.2

350 18

351 18.27

400 .001 53.39 .001 67.85 1.89 20.15 26.17 .001 .001 4.75

410 4.74 3.2

450 2 16.12

500 108.59 23.45 33.86

550 2.48 9.5

600 3.96 12.34 4.99 10.44 5.63 5.98 2.86 .001 11.73 14.95

610 2.98 .001 23.57 7.08

615 1.85

650 .79 6.98

700 11.58 70.05 26.37 2.21 7.26 17.68 41.3 16.89 16.74

709 17.14 .94 40.4 .001 34.37 .87 .001 .001 6.04 11.79

719 31.43 45.12 8.25 .07 .001 .001 .001 .001 .001 7.79

750 3.06 31.66

800 4.83 12.09 6.68 42.53 24.77 18.11 24.32 58.82 39.99

809 6.69 9.26 18.93 31.45 17.89 1.79 .001

850 .63 .001

900 19.53

903 .001 62.59

908 5.58

910 .001 .001 .23

920 .001

950 4.57 1.04

1000 21.47 .001 .001 41.83 9.3 21.55 22.11 18.53 .001

1009 .001 .001 .001 27.6 .001 7 .001

1018 .001 63 .001 .001 .001

1025 68.91

1932 34300

2131 15000

2163 13000

2164 1000

2170 60000

2250 1.32 1.17 .77 1.11 .94 .93 .99 1.42 1.18 1.33 1.12 2.23

2262 1.73 3.3 .96 1.72 2.82 1.03 2.69 1.65 1.33 1.73 .62 1.1

CANDIDATE #2

31 3 2 0 0 0 2 0 0 2000 0 .3 0 0 0 2 1 0 0 0 17 15 153

311 30.37 38.1 59.43

400 .001 53.59 .001 67.85 1.89 18 26.17 .001 .001 4.74

500 26.26 15 17.8 17.8

550 .5 .001

709 17.14 .94 30 .001 34.37 .87 .001 .001 6.04 11.79

1019 .001 .001 .001 27.6 .001 5 .001

2121 80684

2122 18201

CANDIDATE #3

16 2

19 250

20 12.5

403 99.6

2121 82000

APPENDIX IV

SUMMARY OF SYNTHESIS MODEL RESULTS

ITEM	SHIP #1	SHIP #2	SHIP #3
LBP (ft)	408.00	408.00	408.00
Beam (ft)	42.01	41.57	41.43
Draft (ft)	15.61	14.96	15.20
D 0 (ft)	34.58	34.58	34.58
D 10 (ft)	30.50	30.50	30.50
D 20 (ft)	30.91	30.91	30.91
D AVG (ft)	33.17	33.17	33.17
C_P	.59	.59	.59
C_X	.75	.75	.75
VCG Full Load (ft)	18.05	17.93	17.82
L/B	9.71	9.81	9.85
B/H	2.69	2.78	2.72
Range (NM)	4500.00	4500.00	4500.00
Sustained SHP	40230.00	40230.00	40230.00
Endurance SHP	6666.7	6453.99	6485.49
Max Sustained Speed (kts)	31.51	32.19	32.03
Accomodations	185	185	185
Installed Electrical (KW)	4000	4000	4000
Full Load Displacement (tons)	3430.51	3252.41	3294.47
Light Ship Displacement (tons)	2583.74	2400.38	2439.47
Variable Loads (tons)	777.87	783.12	786.27
Weight Margin (tons)	68.91	68.91	68.91
Weight Group 1 (tons)	1212.56	1157.83	1165.00
Weight Group 2 (tons)	200.56	198.11	229.86

ITEM	SHIP #1	SHIP #2	SHIP #3
Weight Group 3 (tons)	193.44	77.36	77.36
Weight Group 4 (tons)	116.13	116.13	116.13
Weight Group 5 (tons)	449.0	438.62	438.62
Weight Group 6 (tons)	318.78	318.78	318.78
Weight Group 7 (tons)	93.54	93.54	93.54
Volume Total (ft^3)	485367	464367	467928
Volume Hull (ft^3)	374662	353662	357223
Volume Superstructure (ft^3)	110705	110705	110705
Cruise KW	2172	2113	2126
Battle KW	1720	1663	1672
24 Hour Average KW	1262	1208	1219

WEIGHT GROUP #	SHIP #1	SHIP #2	SHIP #3
100	257.5	245.4	248.3
101	140.0	130.5	132.8
102	0.	0.	0.
103	72.7	68.4	69.4
107	320.0	329.0	320.0
111	30.4	30.4	30.4
112	38.1	38.1	38.1
113	94.1	59.4	59.4
114	117.8	123.6	124.6
115	39.4	39.4	39.4
116	0.	0.	0.
117	0.	0.	0.

WEIGHT GROUP #	SHIP #1	SHIP #2	SHIP #3
118	0.	0.	0.
119	39.2	39.2	39.2
120	3.2	3.2	3.2
121	0.	0.	0.
122	1.7	1.7	1.7
123	18.8	18.8	18.8
125	0.	0.	0.
127	.8	.8	.8
128	7.1	7.1	7.1
150	18.0	18.0	18.0
151	18.3	18.3	18.3
GROUP 1 TOTAL	1212.6	1157.8	1165.0
200	0.	0.	0.
201	53.4	53.4	53.4
202	0.	0.	0.
203	67.8	67.8	99.6
204	1.9	1.9	1.9
205	20.1	18.0	18.0
206	26.2	26.2	26.2
207	0.	0.	0.
208	0.	0.	0.
209	4.7	4.7	4.7
210	4.7	4.7	4.7
211	3.2	3.2	3.2
250	2.0	2.0	2.0

WEIGHT GROUP #	SHIP #1	SHIP #2	SHIP #3
251	16.1	16.1	16.1
GROUP 2 TOTAL	200.3	198.1	229.9
300	108.6	26.3	26.3
301	23.4	15.0	15.0
302	33.9	17.8	17.8
303	17.8	17.8	17.8
350	2.5	2.5	2.5
351	9.5	9.5	9.5
GROUP 3 TOTAL	193.4	77.4	77.4
400	4.0	4.0	4.0
401	12.3	12.3	12.3
402	5.0	5.0	5.0
403	10.4	10.4	10.4
404	5.6	5.6	5.6
405	6.0	6.0	6.0
406	2.9	2.9	2.9
407	0.	0.	0.
408	11.7	11.7	11.7
409	14.9	14.9	14.9
410	3.0	3.0	3.0
411	0.	0.	0.
412	23.6	23.6	23.6
413	7.1	7.1	7.1
415	1.8	1.8	1.8
450	.8	.8	.8

WEIGHT GROUP #	SHIP #1	SHIP #2	SHIP #3
451	7.0	7.0	7.0
GROUP 4 TOTAL	116.1	116.1	116.1
500	11.6	11.6	11.6
501	70.0	70.0	70.0
502	26.4	26.4	26.4
503	2.2	2.2	2.2
504	7.3	7.3	7.3
505	17.7	17.7	17.7
506	41.3	41.3	41.3
507	16.9	16.9	16.9
508	16.7	16.7	16.7
509	17.1	17.1	17.1
510	.9	.9	.9
511	40.4	30.0	30.0
512	0.	0.	0.
513	34.4	34.4	34.4
514	.9	.9	.9
515	0.	0.	0.
516	0.	0.	0.
517	6.0	6.0	6.0
518	11.8	11.8	11.8
519	31.4	31.4	31.4
520	45.1	45.1	45.1
521	8.2	8.2	8.2
522	.1	.1	.1

WEIGHT GROUP #	SHIP #1	SHIP #2	SHIP #3
523	0.	0.	0.
524	0.	0.	0.
525	0.	0.	0.
526	0.	0.	0.
527	0.	0.	0.
528	7.8	7.8	7.8
550	3.1	3.1	3.1
551	31.7	31.7	31.7
GROUP 5 TOTAL	449.0	438.6	438.6
600	4.8	4.8	4.8
601	12.1	12.1	12.1
602	6.7	6.7	6.7
603	42.5	42.5	42.5
604	24.8	24.8	24.8
605	18.1	18.1	18.1
606	24.3	24.3	24.3
607	58.8	58.8	58.8
608	40.0	40.0	40.0
609	6.7	6.7	6.7
610	9.3	9.3	9.3
611	18.9	18.9	18.9
612	31.4	41.4	31.4
613	17.9	17.9	17.9
614	1.8	1.8	1.8
615	0.	0.	0.

WEIGHT GROUP #	SHIP #1	SHIP #2	SHIP #3
650	.6	.6	.6
651	0.	0.	0.
GROUP 6 TOTAL	318.8	318.8	318.8
700	19.5	19.5	19.5
703	0.	0.	0.
704	62.6	62.6	62.6
708	5.6	5.6	5.6
710	0.	0.	0.
711	0.	0.	0.
712	.2	.2	.2
720	0.	0.	0.
750	4.6	4.6	4.6
751	1.0	1.0	1.0
GROUP 7 TOTAL	93.5	93.5	93.5
800	21.5	21.5	21.5
801	0.	0.	0.
802	0.	0.	0.
803	41.8	41.8	41.8
804	9.3	9.3	9.3
805	21.5	21.5	21.5
806	22.1	22.1	22.1
807	18.5	18.5	18.5
808	0.	0.	0.
809	0.	0.	0.
810	0.	0.	0.

WEIGHT GROUP #	SHIP #1	SHIP #2	SHIP #3
811	0.	0.	0.
812	27.6	27.6	27.6
813	0.	0.	0.
814	7.0	5.0	5.0
815	0.	0.	0.
816	461.9	522.7	555.9
817	83.6	0.	0.
818	0.	0.	0.
819	63.0	63.0	63.0
820	0.	0.	0.
821	0.	0.	0.
822	0.	0.	0.
GROUP 8 TOTAL	777.9	783.1	786.3

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